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STUDIES ON THE PHYSICS AND CHEMISTRY OF ESTUARINE WATERS IN CHESAPEAKE BAY*

By

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Estuarine waters are understood to be those water masses which by virtue of their position are directly subject to the combined action of river and tidal currents. They may be considered to reflect certain dominant forces as well as progressive trends that determine their individualistic though changing hydrographic as well as biologic properties. The factors that lend individuality to these bodies may exhibit profound differences in different latitudes and yet, in certain fundamental respects, the waters possess important characteristics in common. As compared with off-shore ocean waters, they lack constancy in that they possess characteristic horizontal and vertical gradients of physical and chemical conditions subject to more pronounced changes in space and time. The magnitude of the seasonal variations will vary according to latitude. Again, estuarine waters may be characterized by their rapidity of response to changing external conditions. In comparison with oceanic waters, they are subject to changes by the operation of relatively minor forces over shorter time intervals.

Certain inherent physical and chemical properties of estuarine waters clearly differentiate them from typically fresh or salt waters. Their temperature, salinity and turbidity characters are distinctly not homogeneous. The factors governing their movements are of a complex nature. In open ocean mass-distribution, wind, and internal friction are the predominant forces involved in the motion, with mass-distribution providing an approximate index to the movement itself. In estuarine conditions the momentum of

*Contribution No. 21 of The Chesapeake Biological Laboratory.

river and tidal currents achieves an importance it does not attain in open waters, and a distortion of the free surface by a "stau-wasser" phenomenon resulting from the outflow of rivers is superimposed upon the internal mass-distribution, so that the latter becomes quite useless as an index to the actual flow and often plays only a very minor role in determining the movements of the water. That the biochemical and biophysical processes taking place in the estuarine subsurface waters differ markedly from those in the more stable ocean waters is to be expected. The accumulation of certain nutrient salts in waters of estuaries and the atypical character of their vertical distribution tend to show further the changing character of the factorial complex so representative of these waters. Atkins (1926), Harvey (1926), Lucas (1929), Gaardner and Spärck (1932) and Riley (1937) have provided much information on these and allied aspects of estuarine conditions.

The Chesapeake Bay, extending in a north-south direction for about 290 kilometers and possessing numerous tributaries, affords almost ideal conditions for investigating problems peculiar to estuarine waters. Studies in progress since June, 1936, have given a general picture of certain physical and chemical characteristics of the river and bay waters in the vicinity of Solomons Island, Maryland. Attention has been given to the horizontal, seasonal, vertical and hourly variations in respect to temperature, chlorinity, dissolved oxygen and certain nutrient salts. The dominating effect of turbidity in moulding the factorial components affecting the productivity of these waters is stressed.

Recognizing the need of an understanding of the fundamental conditions underlying the basic productivity of estuarine waters, the Chesapeake Biological Laboratory, since 1936, has dedicated funds and a large part of its facilities to the prosecution of hydrographic studies in the Chesapeake Bay and certain of its tributaries. Several persons as well as institutions have generously contributed to the development of this work. The Director of the Laboratory, Dr. R. V. Truitt, Professor of Zoology in the University of Maryland, has been most liberal in offering continuous support and encouragement during the period of the investigation. Thanks are expressed to Dr. H. J. Patterson, Director of the Experiment Station of the University of Maryland for a Grant-in-Aid of this research; to Dr. L. B. Broughton, Head of the Chemistry Department in the University of Maryland, for a loan of certain chemical equipment; to Mr. Harry F. Brust for carefully reading the manuscript and offering constructive criticisms; to Messrs. Carroll B. Nash and F. W. McNall who assisted in the collection and analysis of samples; and, to Captain Harvey Mister whose careful attention in the collection of samples proved most helpful to the investigation. Thanks are also expressed to the U. S. Coast and Geodetic Survey and the Woods Hole Oceanographic Institution for the loan of equipment needed at the beginning of the work.

METHODS

Samples were collected by means of a Kemmerer water bottle. Subsurface temperatures were recorded with reversing thermometers and standard procedure was followed in making field observations. Over a short distance and within a close time interval, variations in the physical and chemical properties of the Chesapeake waters are great as compared with oceanic conditions. For this reason, the high degree of exactitude demanded in many oceanographic studies is not always required. The salt errors are of such magnitude that corrections must usually be made. The analytical methods employed are cited in the discussion of the several components that were analysed. Reference to specific details of procedure and method are purposely reserved for longer treatment in a subsequent paper.

GENERAL DESCRIPTION OF THE REGION

Chesapeake Bay waters possess two dominant characteristics—a gradual horizontal gradient and a distinct vertical stratification with respect to its hydrographic features (Cowles, 1930). These distinguishing properties are the result of two principal modifying influences that determine, largely, the incidence of all other factors, namely, river inflow and ocean inflow. The magnitude of the effect of these respective forces on the conditions at any single place in the Bay at any one time is not known. Their biological import is, however, very great (Compare Newcombe, 1935). Figure 25 shows the relative size of the six major river systems and the numerous smaller tributaries that flow into the Bay draining a considerable watershed (Table I). The entrance from the ocean is in an approximate north-south direction being about 10 nautical miles in width. The mean annual rainfall on the Chesapeake is 45 inches and the evaporation has been assumed to be 60% of the rainfall. Some more recent calculations have indicated that the annual evaporation is about equal to the annual rainfall (Table II) (Wells, Bailey and Henderson, 1929).

The salinity decreases gradually from about 24–30°/$_{oo}$ (chlorinity 13–17°/$_{oo}$) near the mouth (surface) to about 4–7°/$_{oo}$ (chlorinity 2.2–3.9°/$_{oo}$) in the latitude of Baltimore near the headwaters. Frequently, the chlorinity of the bottom waters may approximate twice that at the surface in the deeper parts of the Chesapeake. It is believed that there is a slow movement of relatively heavy oceanic water up the deeper channels of the Bay accompanied by an outward surface flow. Detailed knowledge of the major water movements in the Chesapeake is lacking.

It has been estimated that the average outward current is about 0.3 nautical mile per hour, the rate varying with the cross-section of the Bay. A given phase of the tidal impulse takes place in the latitude of Baltimore about nine hours later than at Cape Charles (Wells, Bailey and Henderson,

Figure 24. Locations of principal sampling stations (numbered points) in the Patuxent River. Station 1 is about 38° 18′ N. lat. and 76° 25′ W. long.

TABLE I

ANNUAL FRESH WATER INFLOW TO THE CHESAPEAKE BAY*

Region	*Drainage area Square Miles*	*Mean rate of contribution Second-feet*
Susquehanna River Basin	27,400	41,300
West shore of Bay between Susquehanna and Potomac Rivers	2,390	3,230
Potomac River Basin	14,140	14,850
Rappahannock River Basin to and including the Piankitank River Basin	29,000	3,150
York and James River Basins to Cape Henry	13,315	15,440
East Shore of Bay between Susquehanna River and Cape Charles	3,980	5,580
Total	64,125	83,550

* Data from U. S. Geol. Water-Supply Paper 234, p. 54, 1909, summarized in U. S. Geol. Survey Professional Paper 154 C, p. 109, 1929.

Figure 25. Bathymetric chart of Chesapeake Bay (Data from U. S. Coast and Geod. Survey maps).

1929). Near Annapolis, surface and bottom flood velocities approximate 0.51 and 0.41 knot per hour, respectively, whereas at the mouth of the Bay the corresponding rates of flow are 1.42 and 1.21 knots according to measurements of the U. S. Coast and Geodetic Survey (Haight, Finnegan and Anderson, 1930).

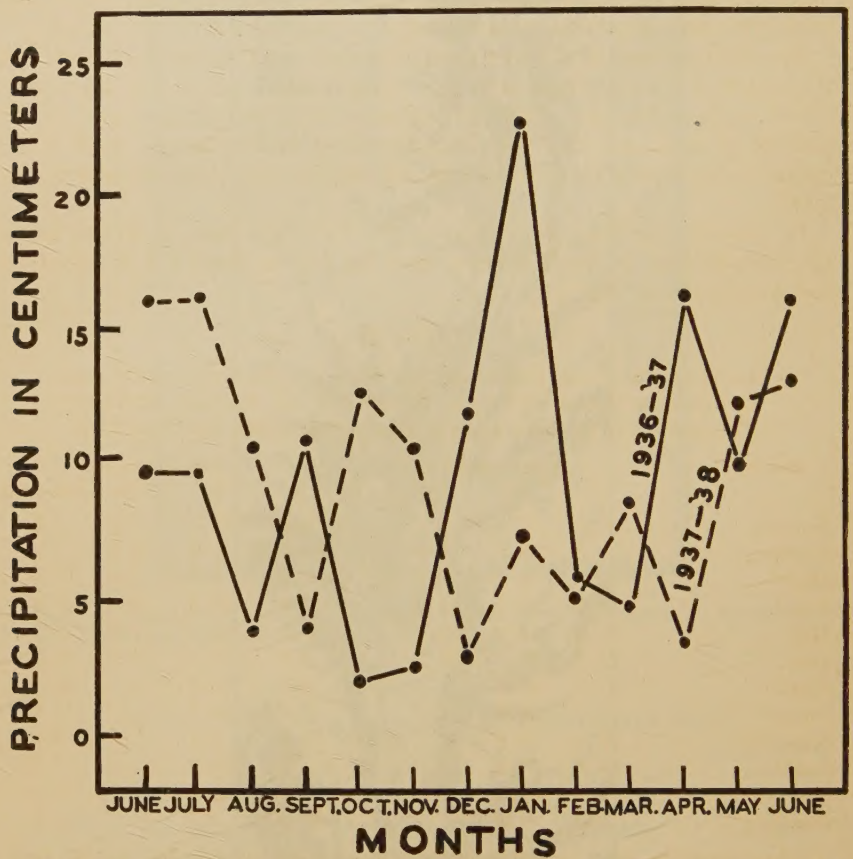

Figure 26. Monthly mean precipitation at Solomons Island, Maryland, during period June 1936–June 1938. (Data from U. S. Weather Bureau Service).

The Bay is characterized by a relatively narrow, deep channel (depth usually between 20 and 40 meters) extending lengthwise and having extensive shallow areas on both sides (Fig. 25). Deep holes ranging in depth from 30 to 40 meters are fairly common. The bottom is typically estuarine being generally very muddy. The shores, on the contrary, are sandy (Cowles, 1930).

Monthly variations in water temperatures are relatively large but the surface-bottom differences rarely exceed 4° C. It should be pointed out that, whereas in the ocean variations in temperature are most important in governing variations in density, the distribution of densities in Chesapeake Bay are mainly dependent upon salinity variations. To the extent that mass distribution exerts a modifying influence upon the water movement in the Bay this can therefore be regarded as essentially a salinity effect.

The drainage area of the river comprises about 1500 square kilometers and the length of the river measured in a straight line is about 130 kilometers. The river basin includes a hilly and rolling country without lakes and the soil consists of sand and clay with some limestone in local areas. Low shores gently rising toward the interior characterize the area (Bonsteel and Burke, 1907).

In general, the tidal amplitude in the Patuxent area, as in the entire Chesapeake Bay, is small varying from 1.4 feet at Station 5 to about 1.7 feet at Station 16 (Fig. 24).

TABLE II

MONTHLY MEAN AIR TEMPERATURES* (°C) AND PRECIPITATION** (CM.) RECORDS FOR SOLOMONS ISLAND, MARYLAND AND AVERAGE MONTHLY PRECIPITATION RECORDS DURING PERIOD 1900–1935 FOR MARYLAND

Month	*Temperature*			*Precipitation*			
	'36	'37	'38	'36	'37	'38	1900–1935
January	0.4	7.6	3.2	16.0	22.6	7.3	8.3
February	– 1.3	3.8	6.0	10.9	5.9	5.1	7.4
March	8.9	6.1	9.9	8.2	4.8	8.6	9.0
April	11.7	12.5	14.6	7.2	16.2	3.5	8.8
May	20.0	19.2	18.6	2.8	10.2	12.2	8.7
June	23.2	24.6	23.0	9.8	16.2	13.2	10.2
July	26.2	25.9		9.8	16.2		10.6
August	26.7	26.3		3.8	10.7		11.6
September	23.2	20.8		10.9	4.1		8.0
October	17.4	14.3		2.0	12.9		7.6
November	9.3	9.3		2.5	10.6		6.6
December	5.3	4.2		11.9	2.9		8.3

* Each monthly mean air temperature represents the mean of the average maximum and the average minimum daily air temperatures for the month.

** As a rule, observations are made late in the afternoon near sunset and precipitation recorded is for the 24 hours ending at time of observation. (Date from U. S. Weather Bureau Service.)

Water temperatures exhibit relatively rapid changes. Table II shows that during 1936 and 1937, the highest mean monthly temperatures were during July and August and the lowest temperatures occurred in January and

February. The variations in precipitation are shown in Table II and Fig. 26.

Consideration has been given to the lower 50 kilometers of the river and that section of the Bay opposite the river mouth (Fig. 24). The depths of the Bay stations are as follows: number 1, 20 meters; number 2, 14 meters; and number 3, 8 meters. As would be expected, the river waters exercise an important influence on the water conditions at Stations 2–8, the records from which constitute the basis for most of this paper.

RESULTS

The physical and chemical aspects of this work conducted during the period from June, 1936, to June, 1938, are summarized here. In many instances, insufficient records are available and not enough time has elapsed to permit conclusive statements with respect to the hydrographic features of the region. However, certain properties of these waters are well defined, revealing factorial interrelationships which may prove constructive in understanding related biological phenomena.

Temperature

The thermal characteristics of immediate concern are the magnitudes of variation in the seasonal trends and hourly fluctuations at a specified point. In respect to air temperatures, seasonal fluctuations at this laboratory indicate fairly similar annual trends during the two years of study. (Table II, Figures 27 and 28.) These temperatures indicate a truer picture than that shown by plotting air temperatures taken when sampling at the several stations. Although the Laboratory is approximately 14 kilometers from Station 1, 10 kilometers from Station 2, and about 3 kilometers from Station 5, the larger number of records per month more than compensates for the discrepancy due to distance.

The trend of the water temperatures at Station 1 for the two year period is shown in Figure 27 (Table III). No records are available for the months January–April (inclusive), 1937.

The monthly trends are quite clear. Those at Stations 1 and 2 (Table IV) are substantiated by comparable records for Stations 3 and 5 and more especially by the constantly recorded temperature records taken off the Laboratory pier. Expectedly, there is some variation due to the distance from Station 1, however, the corresponding nature of the trend is corroboratory.

The seasonal trend of temperatures appears to be characterized by a rather conspicuous drop during October and November, a fairly uniform low until March when, sometimes early and sometimes later in the month, the temperatures start upward and continue throughout April and May

with a more gradual rise during June and July attaining a peak in August. There is a slight decline during September preceding the drop in October.

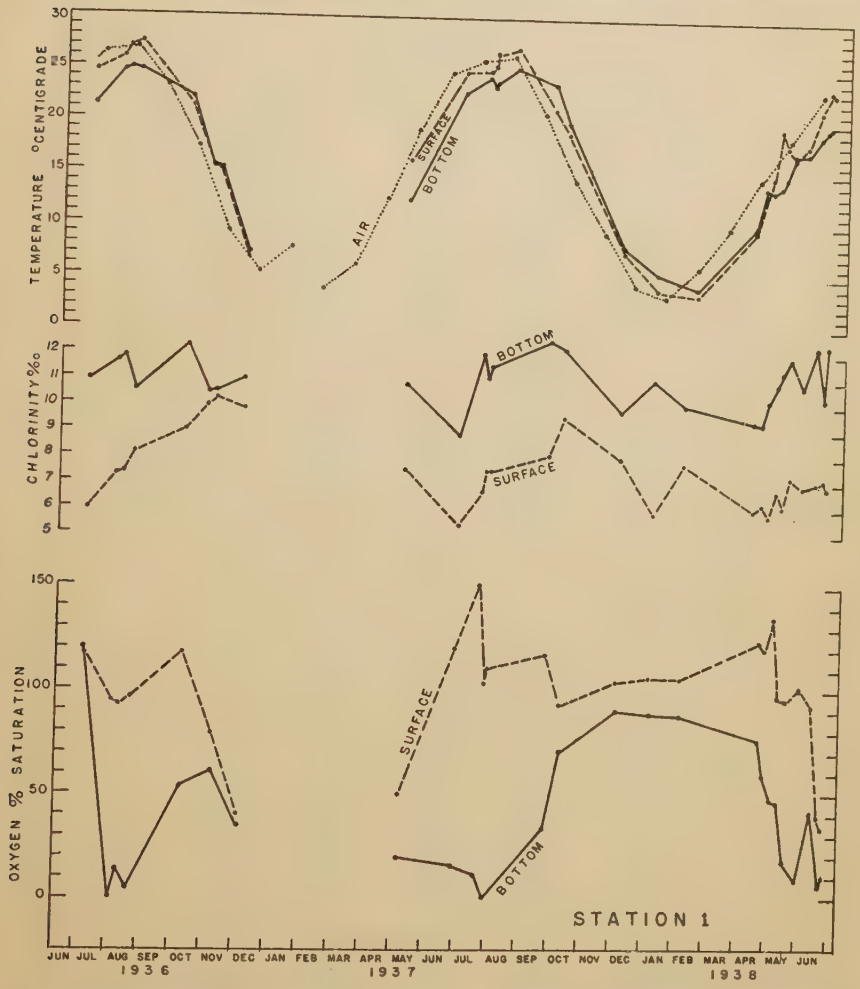

Figure 27. Seasonal variations at Station 1. Air, surface, and bottom temperatures at top. Surface and bottom chlorinities in middle, and relative oxygen contents in lower diagram.

It has been clearly established that the degree of vertical stability developed in these waters as a result of density stratification is such as to render negligible any mixing tendency due to thermal differences. From

late September until about the middle of April surface temperatures are characteristically lower than those at the bottom.

TABLE III

TEMPERATURE, CHLORINITY AND OXYGEN CONDITIONS AT STATION 1 DURING PERIOD JUNE, 1936–JUNE, 1938

Date	Temperature °C.		Chlorinity °/oo		Dissolved Oxygen cc. per liter		% saturation	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
7/7/36	24.5	21.3	5.97	10.92	6.69	6.94	116.7	120.6
8/3	25.9	24.6	7.27	11.66	5.27	0.00	95.2	0.0
8/10	26.8	24.8	7.32	11.84	5.06	0.72	92.5	13.4
8/20	27.4	24.7	8.09	10.53	5.17	0.23	96.8	4.2
10/9	21.2	22.1	9.00	12.24	6.93	2.97	118.0	53.1
10/31	15.2	15.5	9.96	10.44				
11/7	15.2	15.2	10.23	10.48	5.14	3.93	79.6	61.0
12/4	6.8	7.2	9.82	10.99	3.16	2.62	40.8	34.2
5/7/37	16.1	12.4	7.47	10.80	3.26	1.32	49.8	19.4
6/29	24.8	22.8	5.39	8.86	6.91	0.93	120.2	16.2
7/22	24.9	24.3	6.64	12.00	8.66	0.62	150.2	11.4
7/27	25.4	23.3	7.40	11.08	5.71		102.8	
7/29	26.5	23.9	7.46	11.59	5.93	0.00	108.5	0.0
8/19	27.0	25.1						
9/25	21.2	23.7	8.07	12.50	6.95	1.87	117.0	34.3
10/9	18.8	19.9	9.50	12.20	5.66	4.14	92.7	71.1
12/4	7.4	7.8	7.99	9.85	8.11	6.84	103.8	90.5
1/6/38	3.8	5.4	5.81	11.00	9.31	7.05	106.8	89.2
2/5	3.3	4.0	7.76	10.01	9.14	7.23	105.8	87.9
4/12	9.7	10.2	5.97	9.41				
4/21	13.2	13.6	6.21	9.35	8.64	5.15	123.0	76.5
4/28	14.8	13.5	5.75	10.21	7.68	3.97	111.9	59.5
5/6	19.6	14.0	6.68	10.90	8.36	3.10	135.0	47.6
5/11	17.4	14.8	6.08	11.37	6.28	2.99	96.8	46.7
5/18	16.8	17.0	7.27	11.89	6.23	1.08	95.2	17.7
6/1	18.0	17.2	6.91	10.79	6.49	0.60	102.0	8.7
6/14	21.3	18.9	7.06	12.17	5.56	2.48	92.7	41.9
6/23	23.4	19.6	7.04	10.26	2.14	0.40	39.0	6.3
6/24	23.2	19.7	6.80	12.39	1.92	0.49	33.0	8.2

Important in characterizing the thermal conditions of a body of water as well as in interpreting individual temperature records, is the magnitude and trend of the change during succeeding close intervals of time. The nature of surface and bottom variations during hourly intervals is portrayed in Figs. 29 and 30. Pronounced changes may take place within short intervals

due to water movements. The character of these movements becomes apparent on studying the accompanying changes in chlorinity and dissolved oxygen (Fig. 30). The air temperatures exhibit a greater range of variation

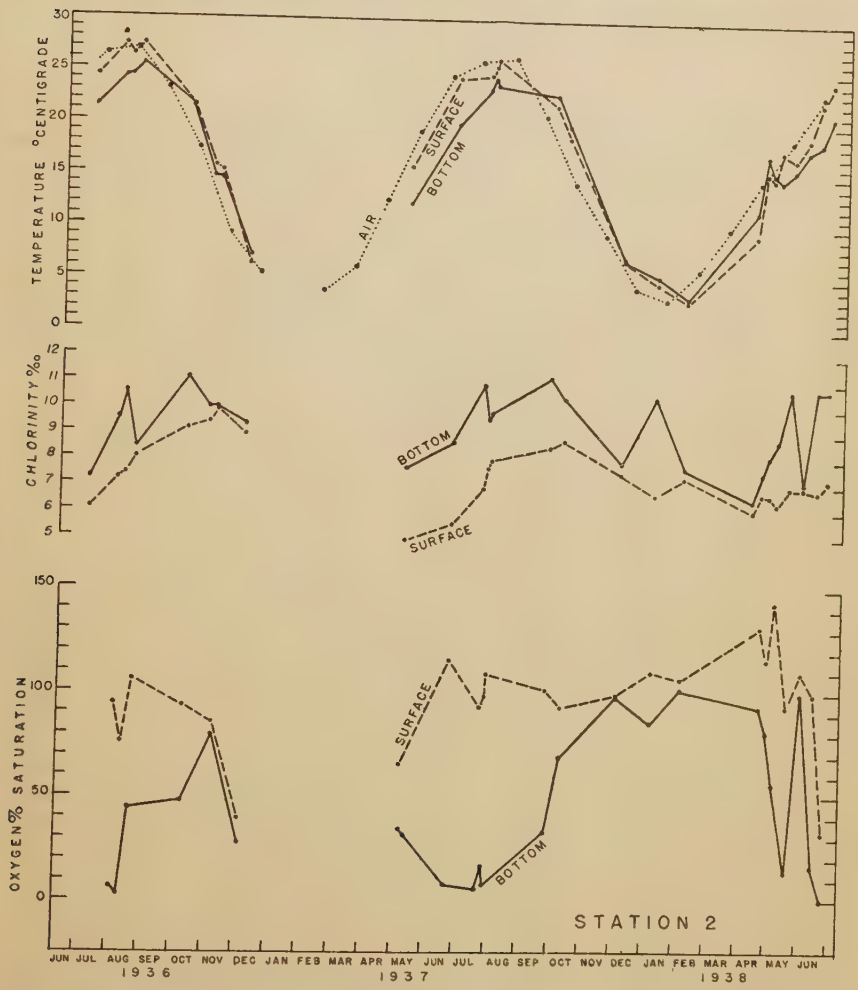

Figure 28. Seasonal variations at Station 2. Air, surface, and bottom temperatures at top. Surface and bottom chlorinities in middle, and relative oxygen contents in lower diagram.

throughout the period (21.5°–28.0° C.) but they are not reflected directly in the water temperatures.

The surface waters during the 24 hour period ranged from 24.1° to 25.0°

C. while those at the bottom ranged from 23.2° to 24.1° C. (Figs. 30 and 31). Vertical variations in water temperature are usually small (Figs. 27 and 28). The successive drops shown are, of course, subject to variation within a short period of time. The general picture is, however, quite indicative of

TABLE IV

TEMPERATURE, CHLORINITY AND OXYGEN CONDITIONS AT STATION 2 DURING PERIOD JUNE, 1936–JUNE, 1938

Date	Temperature °C.		Chlorinity °/oo		Dissolved Oxygen cc. per liter		% saturation	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
7/7/36	24.4	21.5	6.12	7.22	6.69		116.3	
8/3	27.2	24.2	7.27	9.56	5.10	0.35	94.2	6.3
8/10	26.2	24.4	7.40	10.56	4.17	0.14	75.8	2.6
8/20	27.3	25.4	8.03	8.42	5.66	2.48	105.6	44.9
10/9	21.3	21.5	9.12	11.05	5.66	2.72	96.2	47.5
10/31	15.6	14.7	9.38	9.97				
11/7	15.2	14.6	9.93	9.94	5.52	5.14	85.3	78.8
12/4	6.2	7.0	8.92	9.26	3.16	2.14	39.8	27.6
5/7/37	15.7	12.2	4.87	7.64	4.11	2.44	60.6	34.6
6/22	24.3	19.9	5.52	8.64	6.69	0.44	115.6	7.3
7/22	24.7	23.3	6.84	10.82	5.33	0.32	93.8	5.8
7/27	25.5	24.3	7.63	9.57	5.48	0.96	98.7	17.2
7/29	26.2	23.8	7.92	9.79	5.87	0.44	107.3	7.9
9/25	21.8	22.9	8.42	11.16	5.97	1.84	101.9	32.9
10/9	18.7	19.8	8.73	10.38	5.76	4.14	93.5	69.6
12/4	6.9	7.0	7.46	7.87	7.86	7.71	99.2	98.0
1/6/38	4.6	5.4	6.64	10.41	9.31	6.82	110.0	86.0
2/5	3.0	3.3	7.29	7.73	9.42	8.81	107.2	102.1
4/12	9.4	11.8	6.05	6.41				
4/21	15.4	17.2	6.68	7.41	8.88	5.97	132.0	93.5
4/28	14.9	15.4	6.64	8.16	7.88	5.36	116.0	81.8
5/6	17.6	14.6	6.29	8.79	9.24	3.73	143.5	56.2
5/18	16.8	15.8	6.99	10.76	6.02	0.92	92.8	14.5
6/1	18.8	17.6	6.93	7.12	6.93	6.42	110.0	100.0
6/14	22.3	18.4	6.85	10.72	5.86	1.02	99.0	16.8
6/24	24.1	20.9	7.22	10.75	1.89	0.03	33.0	0.5

conditions occurring in June. The difference between surface and bottom temperatures is greatest in summer, when it averages around 3° C. in the deeper waters. Differences greater than 4° are reported rarely.

CHLORINITY

The seasonal variations in the stability of the Chesapeake waters are due largely to the density stratification. In the Solomons Island region, the

variations throughout the year are great in respect to both surface and bottom waters (Fig. 27 and 28). Surface waters usually range in chlorinity between 5 and 8°/₀₀. The highest values obtain during October–December when the surface-bottom differential is least. The bottom waters range in chlorinity between 9 and 13°/₀₀, the annual average for this region being

TABLE V

HOURLY CHANGES IN THE WATERS AT STATION 6 ON JULY 5–6, 1937

Time	*Temperature* °C.		*Chlorinity* °/₀₀		*Dissolved Oxygen* cc. per liter		*% saturation*	
	Surface	*Bottom*	*Surface*	*Bottom*	*Surface*	*Bottom*	*Surface*	*Bottom*
6:15 AM	24.3	23.8	5.76	5.84	5.44	1.79	94.3	30.7
7:15 "	24.3	23.6	5.73	7.59	5.45	2.16	94.4	37.8
7:45 "	24.3	23.8	5.71	7.50	5.60	1.81	96.9	31.6
9:05 "	24.5	23.9	6.05	7.48	4.83	2.44	84.1	42.7
10:15 "	24.6	24.0	5.73	5.78	5.48	4.45	95.3	76.7
11:00 "	24.6	24.1	5.70	6.34	6.07	3.29	105.6	57.5
12:10 PM	24.9	24.1	5.75	5.97	6.21	1.14	108.8	19.7
1:00 "	25.0	24.1	5.76	5.97	5.80	5.31	101.7	91.8
2:00 "	24.7	23.3	5.79	7.44	5.82	1.68	101.5	29.1
3:00 "	25.0	23.3	6.01	7.30	5.37	1.90	94.3	32.9
4:00 "	25.0	23.3	5.88	7.95	6.45	1.25	113.2	21.8
5:00 "	24.8	23.2	5.73	7.11	6.13	1.36	107.2	23.4
6:00 "	24.8	23.6	5.71	7.28	6.57	2.57	114.8	44.6
7:00 "	24.4	23.8	5.88	7.37	5.54	1.91	96.3	33.3
8:00 "	24.4	23.8	5.74	7.71	5.67	1.58	98.4	27.7
9:00 "	24.6	24.0	5.74	6.87	6.27	2.73	109.2	47.6
10:15 "	24.6	23.9	5.82	6.56	5.61	3.39	97.8	58.8
11:00 "	24.7	23.6	5.74	6.83	5.23	3.05	91.2	52.8
12:00 "	24.7	23.6	5.86	7.54	5.24	1.57	91.5	27.4
1:30 AM	24.2	23.8	5.61	6.67	5.37	3.58	92.8	62.0
2:30 "	24.1	23.6	6.17	7.87	4.83	3.55	83.7	61.5
3:30 "	24.1	23.6	6.05	6.96	—	3.74	—	64.8
4:30 "	24.6	23.4	5.84	6.79	—	—	—	—
5:30 "	24.3	23.5	6.91	7.14	5.21	—	91.3	—
6:30 "	24.1	23.6	5.87	7.37	—	—	—	—

about 11°/₀₀. The surface and, to a lesser extent, the bottom waters are influenced by seasonal variations in rainfall and tidal conditions. The magnitude of the surface-bottom differences is smaller in the shallow waters of the western shore (Station 2, Fig. 28), but the general trend is similar to that at Station 1. The lower chlorinity of the bottom waters at Station 2 is clearly shown and is representative of the condition that appears to prevail over a wide area of the western shore (Table IV). The lower density

of these waters as compared with that in the deep channel is a fairly permanent condition reflecting the river inflow.

Hourly collections at Station 6 (Fig. 24) depict the character of the changes in chlorinity taking place over a period of 24 hours (Table V, Figs. 29 and 30). The surface range extends from 5.6 to 6.91°/₀₀. At the bottom, chlorinity conditions are more variable due to tidal movements. From about 10 A. M. until 1 P. M., the densities of the surface and bottom waters were very similar whereas at other times, the chlorinity remained comparatively high at the bottom. This condition prevails over wide areas of the region and is reflected in other characteristics of the water such as oxygen and hydrogen-ion concentrations.

Vertical sampling in widely separated parts of the Bay has demonstrated the presence of two principal strata—a surface level of lower chlorinity about 10 to 12 meters in thickness and a lower stratum of relatively high density reaching to the bottom. The width of the transition may vary from about 4 to 16 meters and the bottom waters of higher density not infrequently contain narrow strata of atypically low density (Fig. 31).

Oxygen

With respect to its biological import, the concentration of dissolved oxygen in the Bay waters offers a most fertile field for investigation. By grouping the records for Stations 1, 2, 3, and 5, it has been possible to picture certain annual trends and to demonstrate particular facts about distribution that are of more than general interest. Figs. 27 and 28 illustrate the character of certain seasonal variations during the period June, 1936–June, 1938. The surface variations are marked, ranging from about 35 per cent of saturation to over 145 per cent (Table III). The concentration of bottom waters range from zero up to about 95% of saturation. The seasonal variations in the oxygen concentrations of the bottom waters are significant (Fig. 27). The picture presented in Fig. 28 (Table IV) is essentially the same in spite of the depth being more shallow at Station 2 (14 meters). It seems highly probable that this fairly stable condition is produced by inherent forces of the Bay rather than by waters originating elsewhere. The seasonal trend at Station 5 is very similar. There are certain short interval variations which can be explained on a basis of local mixing resulting from the bottom topography and tidal forces. Low concentrations of dissolved oxygen were found not to occur in the bottom waters of Station 3. This station is typical of shallow water areas on the western shore of the Bay. Proceeding in an upriver direction, the concentration of oxygen in the bottom layers is progressively higher but still lower than that at the surface (Fig. 29). The character of this oxygen distribution warrants some discussion.

Considering the seasonal variations in oxygen content of bottom waters depicted in Fig. 27, it appears that in the deeper parts of this section of the Bay there is a very definite low concentration during summer. This condition seems to develop during May having reached a conspicuous low by June. It remains as late as September rising abruptly during October.

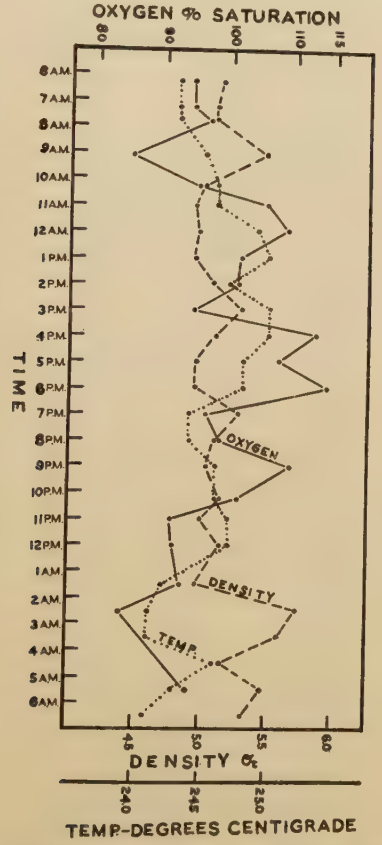

Figure 29. Hourly variations in temperature, chlorinity and dissolved oxygen in surface waters at Station 6 on July 5 and 6, 1937.

This clearly defined oxygen stratification is, as previously pointed out, accompanied by an equally pronounced salinity stratification of opposite gradient, with high salt concentration at the bottom. Whereas, during summer, the oxygen concentration of the surface waters usually ranges between 90 and 105 per cent of saturation, that of the water at depths of 9–14 meters is frequently as low as 35 per cent (2 cc. per liter). Below a 15

meter depth, the concentration is usually under 17 per cent of saturation (1 cc. per liter) and deep water samples are found often to contain no measurable quantity of oxygen (Newcombe and Horne, 1938).

Fig. 31 illustrates the character of the oxygen stratification in the deep channel (Station 1A). These particular surface values are unusually low

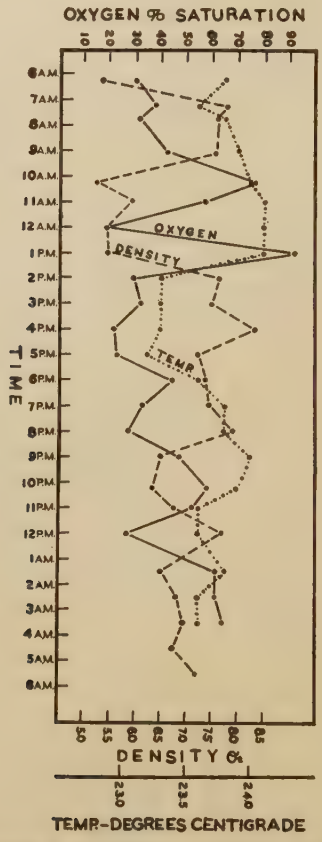

Figure 30. Hourly variations in temperature, chlorinity, and dissolved oxygen in bottom waters at Station 6 on July 5 and 6, 1937.

for this station, in fact for surface concentrations generally. It is seen that the amount of dissolved oxygen decreased rather rapidly with depth until below a depth of about 12 meters the oxygen concentration was under 20 per cent of saturation. These observations have been corroborated by similar series taken during the summer period (Table VI).

An idea of the character of the changes occurring from hour to hour is

presented in Fig. 29 and 30 (Table V). The variations at the surface are expected. Those at the bottom are due, ostensibly, to the tide conditions and represent local movements of surface waters. The low values probably are due to the influx of heavier Bay waters (high in chlorinity and low in

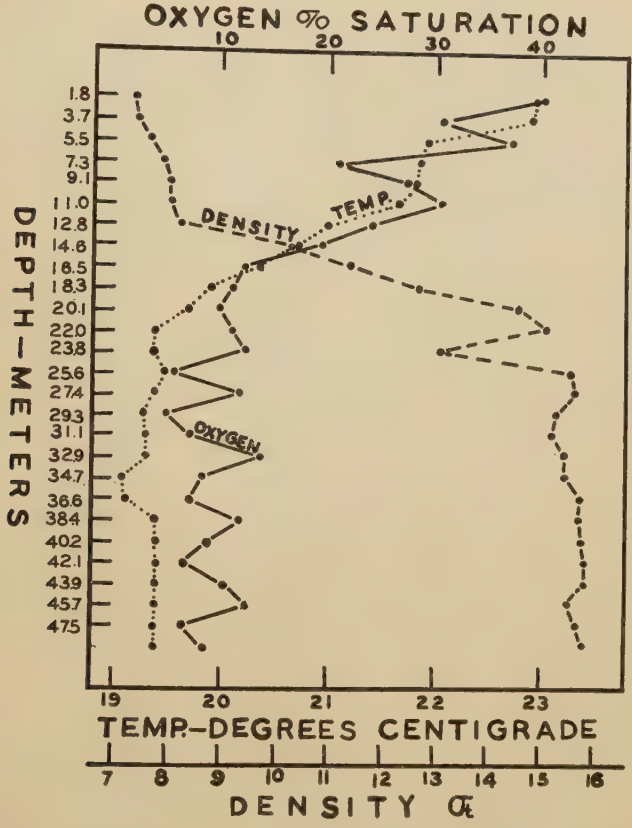

Figure 31. Vertical variation in temperature, density, and dissolved oxygen at Station 1A on June 16, 1938.

oxygen) which under certain tidal conditions are known to move up the river.

Turbidity

Lacking the more desirable photometric apparatus for measuring submarine illumination, use has been made of the Secchi disc. Admittedly, this instrument possesses serious limitations. It does have positive value

in permitting a comparison of two or more regions which differ widely in respect to turbidity (compare Gran and Braarud, 1935, p. 326).

A study of Secchi disc readings made at Station 1 in the deep channel during the two year period indicates that the greater number of readings

TABLE VI

VERTICAL VARIATIONS IN TEMPERATURE, CHLORINITY, AND DISSOLVED OXYGEN AT STATION 1A ON JUNE 16, 1938

Depth	*Temperatures*	*Chlorinity*	*Dissolved Oxygen*	
Meters	*°C.*	*‰*	*cc. per liter*	*% saturation*
Surface	22.9	7.18	2.33	39.80
1.8	22.9	7.21	1.79	30.68
3.7	21.9	7.18	2.20	37.20
5.5	21.8	7.35	1.24	20.95
7.3	21.8	7.40	1.62	27.37
9.1	21.6	7.40	1.83	30.80
11.0	21.0	7.45	1.45	24.10
12.8	20.7	8.92	1.15	19.32
14.6	20.3	9.64	0.73	12.22
16.5	19.9	10.50	0.66	11.19
18.3	19.7	11.84	0.58	9.95
20.1	19.4	12.14	0.65	11.02
22.0	19.3	10.72	0.73	12.38
23.8	19.4	12.54	0.32	5.55
25.6	19.3	12.50	0.69	11.80
27.4	19.3	12.31	0.29	4.98
29.3	19.3	12.24	0.41	7.05
31.1	19.3	12.44	0.81	13.79
32.9	19.0	12.40	0.48	8.21
34.7	19.1	12.61	0.41	7.07
36.6	19.2	12.62	0.69	11.83
38.4	19.2	12.67	0.51	8.78
40.2	19.2	12.71	0.39	6.61
42.1	19.2	12.68	0.60	10.28
43.9	19.2	12.49	0.74	12.53
45.7	19.2	12.63	0.39	6.60
47.5	19.2	12.68	0.50	8.55

fall within the range 2.0–3.0 meters (80–120 inches) a maximum for this station probably being 3.8 m. (150 inches). At Stations 2 and 5, values are usually low, particularly during the spring season. This is to be expected in light of the shallow water and proximity to the Patuxent River outflow (Fig. 24).

The period of minimum turbidity is October to March, inclusive. During the spring and summer periods, there appears to be a progressive increase of

turbidity in the Bay waters due seemingly to an accumulation of suspended matter resulting from the river inflow (Table II). This effect is correlated with the occurrence of more frequent and heavier rainstorms during late spring and summer.

In the Maryland area, that on the average rainfall is greatest from June to September does not in itself account for the increase in turbidity. Rather, the occurrence of frequent and very severe rains at this time favors excessive erosion, particularly from agricultural lands. This results in the contribution of unusually large quantities of suspended matter in a finely divided state to the River and Bay waters. Comparable amounts of precipitation in winter extend over longer periods and their effects are further minimized on account of the low soil temperatures. Pronounced variations in light conditions and rainfall are reflected in the disc readings. The values indicating the minimum penetration at these stations are within the range 1.3–1.6 meters (50–65 inches), whereas up the river at Stations 16 to 21 inclusive, records ranging from 0.5–0.9 meters (20 to 35 inches) are commonly obtained. Many variables tend to introduce variations apart from the actual turbidity of the water. For this reason, the subsequent discussion must limit itself to considering the general indications from these and similar observations elsewhere.

Nutrient Salts

Salt and physical conditions of the waters of this area render difficult accurate colorimetric estimations of certain nutrient substances. Several methods have been used in the case of some analyses and yet certain procedures are far from satisfactory. In this connection, much valuable information has been provided by Thompson and his collaborators and their results have greatly facilitated our chemical work (Thompson, 1932).

Phosphates

At first it was believed that the phosphate content of the Bay waters was exceptionally low. Failure to find any measurable quantities over rather large areas resulted in a more careful examination of the method. It was found that our stannous chloride solution was, in the beginning, too weak, thus accounting for the unexpectedly low phosphate values.

Analyses of samples collected over a large part of the Bay above the Solomons Island region and as far up the Patuxent River as Station 21 have given a general picture of the conditions that prevail during summer seasons. At this time, the surface waters of the Bay have a phosphate concentration ranging frequently from about 0.19×10^{-3} to 0.35×10^{-3} mg. atoms of P per liter. The content of the subsurface waters is higher reaching a maximum at the bottom where values ranging from 0.6×10^{-3} to as high as 1.6×10^{-3} mg. atoms of P per liter often obtain.

In general, the less saline waters of the Patuxent River in its upper reaches are richer in phosphate content than the surface Bay waters. At Stations 17 and 21 on July 19, 1938, the range was between 0.65×10^{-3} and 1.0×10^{-3} mg. atoms of *P* per liter. Samples taken during hourly intervals at several vertical levels have shown marked variation. This is particularly true in the shallower areas subject to considerable mixing. In the Bay proper, consistently higher concentrations characterize the bottom waters.

In these analyses, the Atkins' modification of the Denigès method was employed (Atkins, 1926: Harvey, 1938: Thompson and Pfeiffer, 1935). According to Thompson and Robinson (1932, p. 165) when proper concentrations of acid, ammonium molybdate and stannous chloride are used, this method is capable of detecting 0.001 mg. of phosphorus per liter (0.032×10^{-3} mg. atoms of *P* per liter). Less than 0.005 mg. (0.16×10^{-3} mg. atoms) cannot be estimated accurately. Our precision is of the magnitude of two parts per hundred for average concentrations (Newcombe and Lang, 1939).*

Nitrites

The concentration of nitrite nitrogen was usually within the range 0 to 0.6×10^{-3} mg. atoms of *N* per liter with some values as high as 1.1×10^{-3} mg. atoms per liter. There is some indication of seasonal variations in that during the period July–September, inclusive, the concentrations are highest while lesser amounts are found at other seasons. In general, the bottom concentrations are appreciably greater than those at the surface. The Griess method as modified by Ilosvay has been employed (Buch, 1923). The results presented were reproducible within 0.02×10^{-3} mg. atoms of nitrite nitrogen per liter, over a range of 0 to 0.4×10^{-3} mg. atoms. Above this concentration, the uncertainty is correspondingly greater.

Ammonia

A limited number of ammonia determinations were made over the region in question. No consistent surface-bottom variations seem to prevail. In summer, values ranging from 0 to 8×10^{-3} mg. atoms of ammonia *N* per liter were obtained commonly while the maximum concentration reported is 14×10^{-3} mg. atoms per liter. Wattenberg's modification of the Nessler procedure was used (Wattenberg, 1929).

Silicates

The silicon content of the waters of this region is relatively high as might be expected in waters of such low chlorinity. Examination of data collected

* Care must be exercised in handling phosphate samples on account of the rapidity with which the P concentration changes during storage at the high temperatures that occur here in summer. These authors have suggested the use of CS_2. Recent experiments at this Laboratory show that, to obtain best results, determinations should be made immediately after taking the sample.

during the two year period have not shown any consistent surface-bottom differences. During the period April–October, the silicon concentrations in the Bay are highest ranging from 19×10^{-3} to 30×10^{-3} mg. atoms of *Si* per liter. The winter values commonly fall between 3×10^{-3} and 20×10^{-3} mg. atoms of *Si* per liter. Expectedly, the amounts present in the river waters are uniformly higher than those in the Bay, there being a well defined increase toward the headwaters. At Stations 14 and 21 representative concentrations are about 50×10^{-3} and 120×10^{-3} mg. atoms of *Si* per liter, respectively. The method used for measuring *Si* was that described by King (1931).

DISCUSSION

The analysis of environmental factors operating in estuarine waters is a difficult problem for study. The magnitude of variation with respect to time and distance is very great in comparison with that encountered in ocean or even coastal waters. In the Chesapeake Bay, hydrographic conditions respond much more rapidly to environmental variations than they do in the ocean. Disturbances of minor import to the larger water bodies, in the Bay produce effects of far reaching consequence. Despite the changing complex of external conditions, there have been found to exist certain dominant forces as well as progressive trends that determine the individualistic though changing hydrographic character of the Bay waters.

The trends of air and surface temperatures are fairly similar in character (Fig. 27). The air temperatures during the warmer months are a few degrees higher than the surface, whereas, in winter, they are somewhat lower. A comparison of Fig. 27 and Fig. 28 seems to indicate a similarity of thermal conditions at the surface and bottom. These stations, namely, 1 and 2, are approximately four miles apart, the former being situated in the so-called deep channel of the Bay (Fig. 25) whereas the latter is in shallower water on the western shore. The similar and yet seemingly independent trend of the conditions at Station 2 is indicated by chlorinity and oxygen trends. At Station 3, a characteristically shallow area of the western shore, the seasonal trend of temperature at the surface is quite similar to those at Stations 1 and 2, but the bottom temperature is much higher being relatively close to the surface temperature. At Station 5, the continuity of the seasonal trend of bottom temperatures is frequently disturbed due to mixing resulting from the bottom topography as well as from tidal forces.

The surface-bottom variations are small, rarely exceeding 4° C. The results imply fairly uniform thermal characteristics over the deeper waters of the Bay area studied. The temperatures of the shallow waters of the western shore are slightly higher at the surface and are but slightly lower at the bottom.

Results based on hourly observations at Station 6 indicate a thermal

change of less than 1.0° C. at the surface, namely 24.1° to 25.0° C. during a 24 hour period. The bottom variations are about the same. Sometimes the bottom temperature drops temporarily due to the influx of colder, heavier bay waters during certain tidal phases. In general, a noticeable degree of uniformity prevails (Figs. 29 and 30).

The character of the surface-bottom drop in temperature is by no means well established. Available information shows that this drop is small, being characterized sometimes by one significant bend in the curve and at other times by irregularity (Fig. 31). The changes are gradual. It should be pointed out that from a hydrographic standpoint, chlorinity and oxygen seem to be far more diagnostic in these waters than temperature.

River waters are a dominant factor in modifying the physical and chemical conditions of the Bay waters. Seasonal variations in precipitation influence the surface chlorinity, the turbidity, as well as certain chemical properties of the water. Figs. 27 and 28 clearly show the character of the seasonal variations of the surface and bottom waters. It is significant that the temperature gradient in the fall is unusual. The fact that lower temperatures prevail at the surface than in bottom waters during the fall and winter seasons is due to the pronounced density stratification in which the waters of high chlorinity are at the bottom. The condition at Station 2 is similar to that at Station 1, but quite different from that at Station 3 where the depth is only 8 meters. The situation at Station 3 is probably typical of a large section of shallow water on the western shore. The water is representative of that part of the surface band that covers the denser bottom layer of the deeper areas. At Station 5, which is deeper and with a considerable surface-bottom chlorinity gradient, the trends are in many respects similar to those at Stations 1 and 2. The data signify that the waters quickly recover from the mixing process and return to a stratified condition with respect to density. Observations indicate that the annual chlorinity variations at Station 1 are from 5.81 to 10.23°/$_{oo}$ at the surface and from 8.86 to 12.50 °/$_{oo}$ at the bottom.

Hourly chlorinity changes of the surface waters are much smaller than those at the bottom at Station 6. The bottom changes at this location are influenced by the inflow of heavier bay waters and the outflow of relatively light river water. Variation is marked at this station for which reason it is believed that comparable samples taken at Station 1 would show a more stable condition.

Fig. 31 indicates the abrupt change in density that occurs below a depth of about 14 meters. This seems to be a fairly general phenomenon during summer in the area studied. Its biological significance is important and needs further study.

From a purely biological standpoint, the oxygen distribution is of outstanding importance. The occurrence, during the period June–September,

of what might be termed "oxygen deserts" in the deeper areas investigated has been definitely established (Newcombe and Horne, 1938). It is known that they develop late in the spring, and, when disseminated due to mixing, they may become fully re-established within a period of four days. This characteristic of the bottom layers is an extremely useful hydrographic index of the conditions in the bottom waters. Hourly changes depicted in Fig. 30 are quite marked at the surface due in part to the sky conditions. The bottom variations cannot be explained so easily. The influx of surface waters probably accounts for the high concentration of dissolved oxygen at the bottom. This condition is a temporary one, however, and seems to have been the result of mixing caused by a change in the phase of the tide. It is noted that during the greater part of the twenty-four hour period the oxygen content of the bottom waters is usually under 60% of saturation and conspicuously below the surface concentration.

Fig. 31 shows the vertical distribution of oxygen at Station 1A, near Station 1. It is seen that the decline is quite rapid until a depth of almost 18 meters is reached. Below this level, the concentration is about 4% saturated. Vertical samples taken at several stations in the area indicate that at about a 10–12 meter depth, the concentration of dissolved oxygen starts to decline rapidly. It is not uncommon to find areas in which no measurable quantity of dissolved oxygen is present. Attempts are now being made to explain the factors operating to produce this oxygen anomaly. A similar condition has been shown to exist in certain small Norwegian ponds by Gaardner and Spark (1932). The conditions of salinity and temperature closely parallel those in the Chesapeake Bay. Although concentrations of dissolved oxygen as low as 2.3% saturation were found to exist in the bottom depths of about 4 meters, yet it was on occasion 256% saturation at a depth of 1.5 meters. The data signify that the bottom waters become progressively depleted of oxygen throughout June and July, critically low concentrations occurring in August. It would seem significant that in such small bodies of shallow water, the surface-bottom differences in physical and chemical conditions should be as extreme as in the deeper, Chesapeake Bay waters.

The present data are sufficient to indicate the probable significance of turbidity as a factor modifying the physical and chemical characteristics of the waters in the Solomons Island region. Variations in precipitation, wind movements, etc. tend to be reflected in the amount of particulate matter suspended in the water. Secchi disc readings were made and although they are subject to a wide range of error, it is believed that they may serve to convey some idea of the turbidity which characterizes these waters.

The maximum penetration of light on a bright day, with the sun overhead, is about 3.8 meters in the deeper area of the Bay (Station 1). Approaching the Patuxent River in an up-stream direction, the degree of

penetration on occasions steadily decreases until readings around 0.6 meter are obtained from Station 21 (Fig. 24). Our value of 3.8 meters is very low in comparison with 20 meters which, according to Dr. Horace H. Poole,* is not an uncommon depth for a few miles off the shore at Plymouth, England. Using our maximum record of 3.8 meters, Dr. Poole has calculated roughly the extinction coefficient to be 0.45 which means a reduction to about 1% at 10 meters and 0.01% at 20 meters; values which one would expect to find at three or four times the corresponding depths in the English Channel. In view of this apparent light reduction due to turbidity, it seems possible that a pronounced reduction of phytosynthetic activity resulting from lack of light may be a significant factor in producing the oxygen-poor layer.

It should be pointed out that the high turbidity condition so conspicuous in the river waters is a transient one clearly reflecting precipitation. In the Bay, where there is no conspicuous mass movement of waters, it would appear that there is a gradual accumulative effect during spring and summer resulting from the finely divided suspended particles brought in by the rivers. Evidence in support of this hypothesis is afforded by the work of Newcombe and Lang (1939) on the distribution of phosphates in the Bay.

Thus far, studies on the nutrient salts in the local waters have not progressed sufficiently far to justify a discussion of the seasonal trends. It is possible, however, to indicate the concentrations that most frequently obtain and, to this extent, signify the fertility of the waters in question.

With respect to phosphates, it has already been pointed out that they are, on the whole, very high. Whereas Seiwell (1935), working on the western basin of the North Atlantic, reports values at the surface ranging from 0 to 3 mg. of P per cubic meter (0 to 0.097×10^{-3} mg. atoms of P per liter) and bottom values as high as 300 mg. P_2O_5 per cubic meter (4.2×10^{-3} mg. atoms of P per liter), our surface values during summer commonly range as high as 0.33×10^{-3} mg. atoms of P per liter. The unusually high values, namely, about 2×10^{-3} mg. atoms of P per liter, in the deeper oxygen depleted waters of the Bay are of exceeding interest. These records are as high as those of the river waters which are expectedly high. There is some possibility that phosphates coming from the Patuxent River waters may accumulate in the bottom waters of the Bay during summer when a condition of high turbidity exists. Riley (1937) has shown that the Mississippi River contributes large quantities of nutrient salts into the Gulf of Mexico. Lucas (1929) found concentrations of phosphorus in the bottom waters in the Strait of Georgia usually above 0.10 parts per million of P_2O_5 (1.4×10^{-3} mg. atoms of P per liter). His average value for the surface waters was 0.05 parts per million of P_2O_5 (0.7×10^{-3} mg. atoms of P per liter). For the North Sea, Atkins (1923) reports average values around 0.025 parts per million of P_2O_5

* Personal Communication.

(0.35×10^{-3} mg. atoms of P per liter). It is seen that the Bay waters are richer than those in the ocean in respect to this very important nutrient salt. Available information indicates that the maximum concentrations of phosphate exist during the summer and minimum amounts prevail during winter when the phytoplankton is most abundant and the turbidity is lowest (Newcombe and Lang, 1939).

Results to date indicate a general range of from 0 to 0.6×10^{-3} mg. atoms of nitrite N per liter, higher bottom than surface values and occasional concentrations as high as 1.1×10^{-3} mg. atoms per liter. During July and August, zero values were frequently obtained for the surface waters and the higher concentrations occurred in the bottom waters. Harvey (1926) reported very minute amounts in the English Channel. Orr (1926) reports higher concentration, namely 2 to 10 mg. NO_2 per cubic meter (0.04×10^{-3} to 0.2×10^{-3} mg. atoms nitrite N per liter) for the surface waters of the Clyde Sea area. Rakestraw (1932, 1936) studied the nitrite content of Atlantic waters in the Gulf of Maine, Bermuda, and the Caribbean areas. He concluded that the nitrite concentration varies normally from 0 to 0.35 microgr. atoms per liter (0 to 0.35×10^{-3} mg. atoms per liter). His highest value, 0.91 microg. atoms per liter (0.91×10^{-3} mg. atoms per liter) was obtained in Cape Cod Bay. It appears that our values are higher than those obtained for more saline waters, a condition to be expected in light of the inland and estuarine character of the Chesapeake area.

The concentrations of ammonia N range are, in summer, as high as 14.0 $\times 10^{-3}$ mg. atoms per liter whereas values below 6.0×10^{-3} mg. atoms are obtained usually. In the open sea, values between 10 and 50 mg. NH_3 per cubic meter (0.59×10^{-3} and 2.9×10^{-3} mg. atoms ammonia N per liter) have been reported, whereas Thompson and his associates found less than 10 mg. per cubic meter (0.59×10^{-3} mg. atoms per liter) in the Strait of Juan de Fuca and adjoining waters. The Chesapeake waters are, it would seem, well supplied with ammonia nitrogen during the summer season. Although numerous analyses have been made for nitrate N, the strychnine method employed is not considered to be sufficiently accurate to warrant a discussion of the results.

The silica content of local waters is high as might be expected in waters of this saline concentration. In the upper river stations 20–21, high surface values occur, ranging from 50 to 116×10^{-3} mg. atoms of silicon per liter, whereas, at Stations 14 and 15 (Fig. 24), the concentration is usually around 50×10^{-3} mg. atoms of Si per liter. The waters of the Bay are characteristically lower, varying around 25 mg. atoms of Si per liter during the summer season. The marked fluctuations that occur in the river waters represent a response to rainfall which results in the presence of varying quantities of dissolved and suspended substances in the water. Atkins (1923) reports surface concentrations of SiO_2 varying from 0.2 to 0.6 mg. per liter ($3.33 \times$

10^{-3} to 9.99×10^{-3} mg. atoms of *Si* per liter) while Lucas (1929) states that surface values between 1.0 and 3.0 mg. SiO_2 per liter (17×10^{-3} and 51×10^{-3} mg. atoms per liter) were found generally in the Strait of Georgia.

In general, there is evidence of high concentrations of nutrient salts in the bottom waters during the summer period when light penetration is reduced due to maximum turbidity. The occurrence of minimum phosphates during winter accompanied by minimum turbidity and maximum phytoplankton strongly suggests a cycle of nutrient salts that is the reverse of that in certain ocean waters and reveals the importance of and need for precise light data in interpreting the existing and seasonal variations.

SUMMARY

Certain physical and chemical characteristics of the Chesapeake Bay waters in the region of Solomons Island, Maryland, have been studied during the period, June 1936–June 1938. They have been treated in regard to the following aspects—seasonal trends, surface-bottom variations, the magnitude of hourly changes, as well as the annual maximum and minimum concentrations of various elements.

The seasonal trends of surface and bottom temperatures are depicted in Figs. 27 and 28. The high, summer temperatures remain until about the first week in October after which there is a marked decline of about 10° C. (i.e. from about 25 to 15° C.) until the early part of November. By the first week in December, the surface and bottom temperatures have dropped to about 7° C. During January and February, the lowest temperatures, namely 3 to 4° C., prevail. The abrupt rise of water temperatures during spring takes place in April and May, a level of about 20° C. being reached by the middle of June. The variation from surface to bottom rarely exceeds 4° C. and, during relatively long periods between September and June, the variation is only about one or two degrees Centigrade. Due to the high density of the bottom waters, lower temperatures at the surface than at the bottom are often continuously maintained during winter. The hourly changes in thermal conditions are usually less than 0.5° C.

The chlorinity characteristics of the Bay waters are well defined and of major importance in determining the incidence of other environmental factors. Annual chlorinity variations at Station 1 were found to be from 5.81 to 10.23‰ at the surface and from 8.86‰ to 12.50‰ at the bottom. The dominant characteristic in respect to density distribution is the well-defined vertical stratification. During summer, at about 10 or 14 meters, there is, usually, an abrupt gradation from the less dense surface waters to the bottom stratum of heavier water possessing a relatively uniform chlorinity.

The seasonal trends of oxygen distribution over the area studied reflect surface variations of a very high order of magnitude. Levels as high as 150%

saturation have been reached in January due, probably to phytoplankton abundance, and as low as 33% in summer, due, it is believed, to the mixing of bottom with surface waters. The occurrence during the period June–September of a very low oxygen concentration in the bottom waters over relatively large, deep areas of the Bay is significant. Surface waters unusually low in oxygen are considered to have their origin in the deeper areas of the Bay.

Secchi disc readings taken throughout the year over the area in question, reveal marked seasonal as well as horizontal variations extending from the Bay up the Patuxent River. The extent of the seasonal variations in the Bay is about 2.3 meters and the maximum Bay-River variations is about 3.2 meters. These are marked changes and, despite the inadequacy of this disc for measuring depth of light penetration, they signify the importance that must be assigned to light in reviewing the factorial complex under consideration.

On account of the rather unique bathymetric and topographic conditions that characterize these estuarine waters, some significance is attached to the amount of nutrient salts present in comparison with the ocean concentrations which have been more thoroughly investigated. It has been found that the phosphate content of the Bay waters, in summer, commonly ranges as high as 0.23×10^{-3} mg. atoms of *P* per liter at the surface and 1.0×10^{-3} mg. atoms in the bottom waters. The river waters at the upper stations contain average concentration of about 0.95×10^{-3} mg. atoms of *P* per liter during the summer season. Minimum concentrations obtain during the winter period when turbidity is minimum and the abundance of phytoplankton organisms is maximum.

The results of nitrite analysis indicate a general range of from 0 to 0.6×10^{-3} mg. atoms of nitrite *N* per liter, higher bottom than surface values and occasional bottom concentrations as high as 1.1×10^{-3} mg. atoms per liter. In early summer, zero values frequently obtain in the surface layers of the Chesapeake area.

The concentration of ammonia nitrogen varies from 0 to over 8.0×10^{-3} mg. atoms per liter during the summer season and local variations are pronounced. Available information seems to indicate that the Chesapeake waters are much richer than ocean water, in respect to this nutrient salt, although special study must be devoted to the local nitrogen cycles before definite conclusions can be reached.

The Bay and River waters possess a very high silicon content during summer. The waters in the upper reaches of the river contain concentrations as high as from 50×10^{-3} to 116×10^{-3} mg. atoms of *Si* per liter. The concentrations at the lower river stations and in the Bay are much lower, commonly ranging around 20×10^{-3} to 30×10^{-3} mg. atoms of silicon per liter.

A summary of this work should not be concluded without stating that the Chesapeake Bay estuarine conditions are unique both from a hydrographic and a purely biological standpoint. There are many problems here for the physicist, the chemist and the biologist, alike, all in need of elaboration. If, therefore, some interest has been aroused in the solution of these problems, the present work will have been justified.

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MEASUREMENTS ON THE TRANSPARENCY OF SEA-WATER OFF THE COAST OF SOUTHERN CALIFORNIA

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In a series of papers (*7a, b, c, d, e*) Pettersson has described the construction and use of a transparency meter and has given the results of transparency measurements at several stations in Swedish waters. Two of the main difficulties in determining the transparency of sea-water by measuring submarine daylight arise from fluctuations of the surface intensity and from the rapid decrease of intensity with depth. The transparency meter uses an artificial source of light, thus ensuring constant intensity. The present paper reports transparency measurements for 23 stations off the coast of Southern California.

The essential features of the optical and electrical arrangement are shown in Fig. 32. Light from the source S is collimated by the lens L and is re-

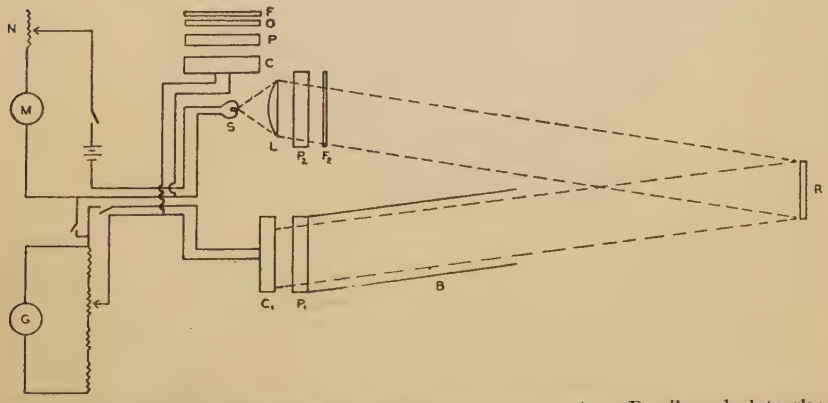

Figure 32. Optical and electrical design of transparency meter. R: silvered plate glass mirror. B: perforated brass cylinder. P, P_1, and P_2: ½″ plate glass. C and C_1: Weston Photronic cell, model 594. S: 50 cp, 12–16 volt automotive headlight bulb. Operated at 14 volts and 3.00 amperes. F, F_2: Schott VG-9 green filter 2 mm. thick. O: opal diffusing glass. M: Westinghouse PX-4 ammeter. G: Weston model galvanometer.

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flected from the mirror R to the photronic cell C_1. Variations of the cell output measure variations of the transparency of the water column traversed. The light source and cell are enclosed in a water-tight casing with sealed glass ports P_1 and P_2. The mirror is carried by rods attached to the casing to give a total path length in water of 184 cm. The instrument was suspended in a horizontal position, thus giving readings for a well defined depth. The casing contained drying agents to prevent condensation on the

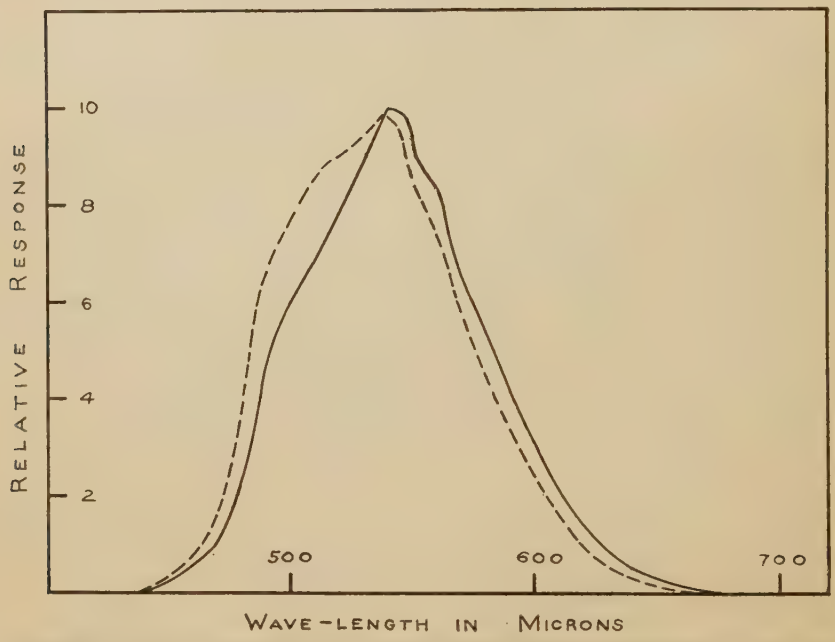

Figure 33. Relative response curve of Photronic cell and filter combination. Full curve: lamp light; dotted curve: sunlight.

inside surfaces of the windows. The horizontal cell C was used to measure natural daylight. A four strand rubber covered cable enters the casing through a stuffing box. Current for the lamp was supplied by storage cells and controlled by the rheostat N. The current was read on the meter M to within .01 amperes. At 3 amperes, the current rating of the lamp, a variation of .01 ampere caused a 2% variation of the cell output. The current delivered by the cell was read on the galvanometer G which was shunted by a universal shunt whose total resistance is the critical damping resistance of the galvanometer. The cell output and resistance of the circuit were such that one always worked on the linear portion of the response curve of the cell. The galvanometer deflections were hence always proportional to

the light intensity incident on the cell. B is a perforated cylinder of sheet brass, 45 cm. long. This cylinder serves to cut out the submarine daylight. The natural light incident on C_1 never amounted to more than 7% of the artificial light.

Filters F and F_2 were used over each cell. If $G(\lambda)$, $H(\lambda)$ and $I(\lambda)$ are the relative spectral response of the cell, the relative transmissivety of the

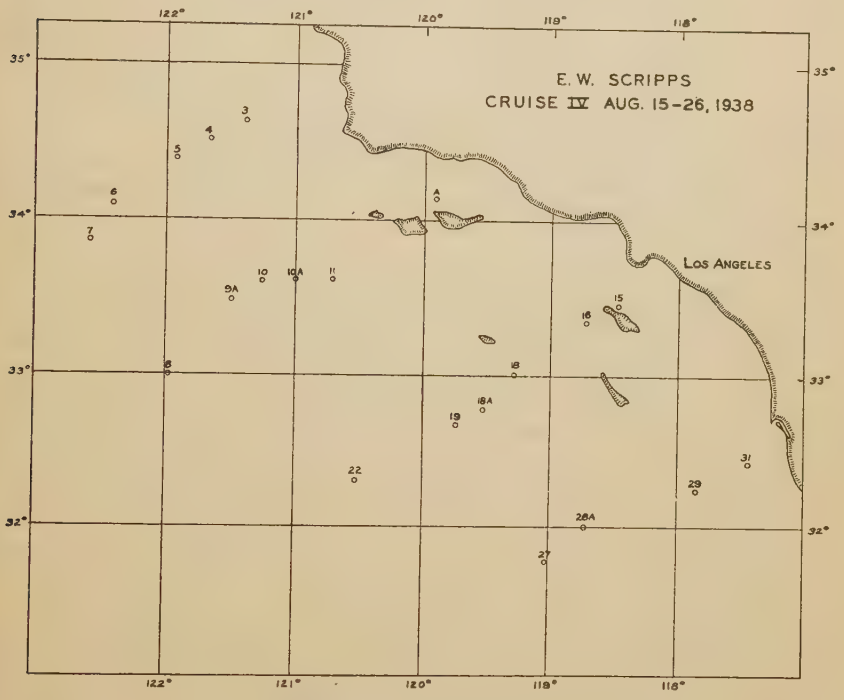

Figure 34. Location of stations.

filter and the relative spectral intensity of the incident light respectively, then $R(\lambda) = G(\lambda)H(\lambda)I(\lambda)$ is the relative spectral response of the cell and filter system to the given incident light. In Fig. 33 are given the curves of $R(\lambda)$ for light emitted by the lamp and for sunlight. Characteristics of the cell, lamp and filter were obtained from their manufacturers. The data for the cell and lamp are for an average product and the characteristics of an individual sample may differ considerably from the average. However, since the transmission factor $H(\lambda)$ controls the shape of the relative response curve, considerable differences in $G(\lambda)$ or $I(\lambda)$ do not materially affect the shape of the curve of $R(\lambda)$. $I(\lambda)$ for sunlight was obtained from curves

given in Duggar's "Biological Effects of Radiation" (4) which are based on data of Abbot's (1).

The relative response curves of $R(\lambda)$ are very similar for lamplight and sunlight. To calculate the relative response curve of the cell and filter combination for the two radiations after they have passed through water, one would establish the function $R(\lambda)e^{-k(\lambda)x} = S(\lambda, x)$ where $k(\lambda)$ is the extinction coefficient. The two curves for $S(\lambda, x)$ will remain similar if x is the same. However, while x is constant at all depths for the transparency meter, for sunlight x increases as the depth, and the response curves will not remain similar to themselves. Extinction coefficients calculated for sunlight and for lamplight will not be the same unless $S(\lambda, x)$ is the same for the two radiations at all depths. The relative energy in sunlight will be increasingly concentrated in the spectral region for which $k(\lambda)$ is a minimum. If this value for $k(\lambda)$ is near the maximum of the response function $R(\lambda)$, $S(\lambda, x)$ for sunlight will only change slowly with increasing depth, and its maximum will not be greatly shifted.

The instrument was operated as a part of the routine hydrographic measurements on the August, 1938, cruise of the Scripps Institution's new boat, the E. W. Scripps. Fig. 34 is a map showing the location of the stations worked. As can be seen, a rectangular area roughly 300 miles parallel and 150 miles perpendicular to the coast was covered. We have thus obtained data on the variation of transparency with depth for an extended body of water. Data on salinity, temperature and plankton are available for all the stations. Besides the stations shown on the map, two others were worked in the vicinity of Monterey Bay, 150 miles north of the area shown. At every station readings were taken at 5 meters, 10 meters, and thereafter every 10 meters down to 60 meters.

The data is presented by the graphs of Fig. 35. Abcissae are values of the galvanometer deflections relative to that at the 60 meter depth for each station. While extinction coefficients are of course proportional to the logarithm of the photo-cell current, variations of the current itself can equally well be used to describe variations in transparency. The locations of Stations 3 to 31 and A are shown in Fig. 34. Station B is five miles off Monterey, C a quarter of a mile offshore. Each point of the graphs represents the average of readings of the instrument as it was lowered and raised. Taking the data as a whole the average deviation of the two readings from their mean value is 4%. The maximum deviation is 30%. In every case the variation was in the same direction, going down or coming up. In many cases the deviations probably arise from the fact that the instrument, for like depths as measured on the cable, is not at the same level coming up as going down due to varying set of the line.

It was impossible to compare the readings at one station with those at another. To do this, one must be able to obtain readings at each station

for some standard condition, say for air. Due to the fact that the beam is not perpendicular to the exit window P_2, its path in water is different from that in air. For use on board boat the path had to be permanently adjusted so that in water the center of the beam struck the center of the photo-cell. This meant that in air only a fraction of the beam was incident on the cell. Under these conditions the cell output was very sensitive to

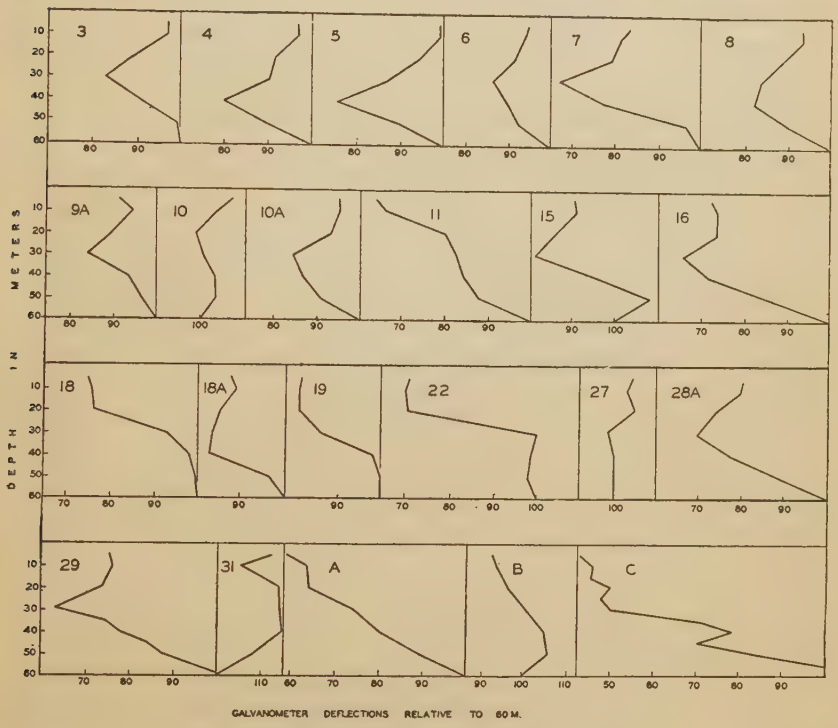

Figure 35. Variation of transparency with depth.

adjustments of the beam. Under the necessarily rough treatment to which the instrument was subject it was impossible to be sure of the beam adjustment from station to station. Pettersson (2) has described a design wherein the beam is normal to the windows, which overcomes this difficulty. Also the instrument readings depend on the cleanliness of the glass surfaces. To obtain consistent readings in air they should be optically clean, and with stations in many cases being worked every two hours it was impossible to accomplish this. In water the windows clean themselves and it is believed that at a single station the readings are a reliable indication of the transparency.

Though differing greatly in detail, the majority of the curves fall into one or the other of two groups: (a) transparency goes through a definite minimum and (b) transparency increases monotonically from the surface down. Stations 3, 4, 5, 6, 7, 8, 9A, 10A, 15, 16, 18A, 28A and 29 belong in the first group and Stations 11, 18, 19, A and C in the second group. All the minima in group (a) occur at either 20 or 30 meters. There appears to be no correlation between this grouping and the location of the stations. The transparency at the remaining stations, namely 10, 27, 31 and B does not appear to follow any definite trend. Station C, at which the range of variation is the greatest is very near shore and the absolute value of the extinction coefficient, as determined from measurements on daylight, was very large at this station.

From the temperature and salinity data, densities have been computed for all stations. There is no clear cut correlation between transparency and density. Pettersson (*7a, b, c, d*), has compared transparencies and salinities and finds in some cases that a marked density boundary, such as commonly occurs within fjords, is accompanied by a sharp minimum in the transparency. He attributes this to the fact that at a density boundary there will be a concentration of organic particles in the uppermost stratum of the denser water in the immediate vicinity of the boundary. At the stations investigated by us there were no density stratifications as marked as those encountered by Pettersson. In the table below are given the densities in terms of $\sigma_t = (\rho_{s,t,o} - 1)10^3$ (where $\rho_{s,t,o}$ is a function of salinity and temperature, but compressibility has been neglected) for a few representative stations.

Sta.	*4*	*7*	*11*	*15*	*29*
0	24.18	24.14	24.33	23.49	23.99
10	24.30	24.30	24.46	23.65	24.09
25	24.38	24.52	24.66	25.24	24.10
50	25.02	25.16	25.39	25.70	25.23
75	25.35	25.45	25.86	25.94	25.65

Though the minimum in transparency at Stations 4, 15 and 29 at 30 or 40 m. may be associated with the maximum slope of the density curve which lies between 25–50 meters, in the case of the other two stations, which have the most marked changes of density, there are no corresponding transparency minima.

Through the kindness of Prof. W. E. Allen plankton counts, together with rough estimates of the amounts of debris, are available for every depth at which transparency measurements were made. These have been compared with the transparency data. For the open-water stations shown in Fig. 34 the plankton densities ranged from 0 to 9,000 cells per liter. These are relatively very small concentrations and in general no definite correlation

has been established between number of plankton and transparency. It was observed, however, with but one exception, that if the difference of the number of plankton between two depths was greater than 2,000 cells per liter, the transparency increased or decreased in the expected direction. This was not, however, the case for Stations B and C where the plankton counts ranged from 0 to 172,000 cells per liter. It is to be pointed out also that for the open-water stations there were variations in transparency up to 20% where plankton densities were negligible throughout the range of depths investigated. At the majority of stations the volume of debris was from 10 to 100 times that of the living plankton, and in general varied in the same manner as the plankton. Where there were differences, what correlation existed between transparency and particle concentration seemed to follow the plankton. Pettersson (*7a, b, c, d*) has investigated the relation between particle concentration and transparency. He finds in some cases that sharp minima in transparency are accompanied by large concentrations of plankton or debris, but in other cases he finds variations in transparency which he is unable to explain on the basis of plankton or detritus content. The plankton concentrations reported by Pettersson vary up to 3,000,000 cells per liter. He finds (*7b, c, e*), however, that in almost every case the transparency and scattering curves are anti-symmetrical, i.e. decreases of transparency are always accompanied by increases of scattering. Where this is not true a coloring agency may be held responsible for the discrepancy; vide Kalle (*6*), James and Birge (*5*). This is not likely to play any significant role in off shore stations. This indicates that the same factors responsible for variations in transparency are responsible for variations in scattering. It would therefore appear probable that suspended materials, too fine to be detected by straining, are involved. This conclusion has been arrived at by Whitney (*8*) on the basis of transparency measurements on lake waters. James and Birge (*5*) point out the existence of suspensoids in lakes (material which does not settle out) and Clarke and James (*3*) discuss this question for sea-water.

If I_0 is the intensity of light emerging from the exit window of the equipment, I_1 the intensity at a depth z_1 and I_2 the intensity at a depth z_2, incident on the entrance window, then:

$I_1 = I_0 e^{-k_1 x}$ and $I_2 = I_0 e^{-k_2 x}$ where k_1 and k_2 are the extinction coefficients for a beam of parallel light at the two depths and x is the path length in water. Dividing, we obtain

$$I_2/I_1 = e^{-(k_2 - k_1)x} = e^{-\Delta k x} \text{ where } \Delta k = k_2 - k_1.$$

Consider determinations of the intensity of submarine daylight as made with the horizontal cell. If I_1' and I_2' are the respective intensities of submarine daylight at depths z_1' and z_2', and I_1'' and I_2'' are intensities at depths z_1'' and z_2'':

$I_2'/I_1' = e^{-k_1'(z_2'-z_1')}$ and $I_2''/I_1'' = e^{-k_2'(z_2''-z_1'')}$ where k_1' and k_2' are the mean vertical extinction coefficients between the depths in question. We would like to compare Δk and $\Delta k'$ where $\Delta k' = k_2' - k_1'$. If they agree it would be possible, given the intensity of submarine daylight at a single depth, to use the transparency meter readings to determine it at all depths. If μ is the true absorption coefficient and α the scattering coefficient: $k = \mu + \alpha$. Now the effect of scattering on the intensity of light incident on the receiving cell is entirely different in the case of the transparency meter than in the case of a cell receiving daylight. In the former, light scattered from the beam is almost completely lost, whereas in the case of daylight, light lost by scattering from one element of path will be regained from another path element. As Pettersson points out, this makes the transparency meter superior to daylight meters for locating masses of suspended material. We can expect agreement between calculations of extinction coefficients from the two types of data only if the scattering coefficient is small compared to the absorption coefficient, or if the scattering coefficient remains constant. Pettersson (*7c*) has compared extinction coefficients obtained in the two ways, using unfiltered cells. He finds the vertical coefficient becomes progressively smaller than the coefficient determined from the transparency meter. This is due to the progressive hardening of the light as the less penetrating wave-lengths are absorbed. In our case, however, reference to Fig. 33 shows that such an effect would be small.

We have made measurements on daylight at Stations 10, 10A, 15, 15A and A.

Station	*10*	*10A*	*15*	*15A*
Depth	50–60	50–60	50–60	50–60
Vert. extinc. coeff.	.060	.061	.046	.049

A

Depth	*Vert. ext. coeff. k'*	*Parallel ext. coeff. k*
20–30 m	.079	.039
30–40	.086	.047
40–50	.082	.032
50–60	.061	.072

The readings at Stations 10, 10A, 15 and 15A are included to give an idea of the absolute magnitude of the vertical extinction coefficients in this body of water. They agree with coefficients obtained two years earlier for several stations in the same region (*6*). The data for Station A shows that the scattering phenomenon is the controlling factor in the extinction coefficients for parallel light.

In conclusion the author wishes to express his appreciation to Dr. H. U. Sverdrup for the opportunity to carry on this work at the Scripps Institution. The author is also indebted to Dr. H. Pettersson for helpful criticisms of the manuscript.

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A RAPID METHOD FOR THE DETERMINATION OF DYNAMIC HEIGHTS (OR DEPTH) AT SUCCESSIVE LOWERINGS AT AN ANCHOR STATION

By

E. F. THOMPSON

Seiwell (1937) has shown that the computed dynamic height at any one place varies considerably with time, independently of the average gradient current system. He has shown that this is due to the short period vertical oscillations known to exist from the work of Helland-Hansen and Nansen (1926) Defant (1932) Seiwell (1937) and others. Seiwell (in course of publication) has further suggested that in any survey designed to establish the dynamic topography of a region, ordinary short stations should be checked by "Anchor" stations* of not less than 26 hours duration. Roughly, the suggestion is that by determining the dynamic height for successive lowerings at the "Anchor" station, the amount of change at any one locality can be found; and hence the degree of significance to be attributed to dynamic differences between ordinary stations defined.

The usual method for determining the dynamic height depends on the use of Bjerknes' and Sandstrom's anomalies. According to Sverdrup (1933), the anomaly is found finally from the equation (1) $\delta = \delta_s + \delta_t + \delta_{s,t} + \delta_{s,p} + \delta_{t,p} + \delta_{s,t,p}$. Values for these six factors are given in Bjerknes' (1910) tables (9H, 10H, 11H, 12H, 13H, and 14H). Even in the most accurate work the quantity $\delta_{s,t,p}$ can be neglected; still the determination of the anomaly involves a great deal of labour and reference to 5 sets of tables. In an attempt to reduce the labour involved Sverdrup (1933) has made use of the fact that the first three terms in the above equation (1) can be combined as

$$\delta_s + \delta_t + \delta_{s,t} = \Delta_{s,t} \tag{2}$$

$$\Delta_{s,t} = 0.02736 - \frac{\sigma_t 10^{-3}}{1 + \sigma_t 10^{-3}} \tag{3}$$

He has constructed tables (Table I and Table 4a and 4b) from which the values of $\Delta_{s,t}$ may be read off from the values of σ_t. This saves a considerable amount of work if the value of σ_t has already been determined, but if this has not been done the saving is relatively small.

As a great deal of trouble has been taken to give the dynamic height "correctly" to the second and even the third place of dynamic centimeters,

* For the purpose of this paper an "Anchor Station" is one at which successive lowerings are made over a considerable period of time without change of position.

it is worth while considering whether such accuracy is warranted by the methods of determination. An error in the standardization of the silver nitrate against the normal water, of $\pm 0.005°/_{oo}$ Cl. is not unusual; yet when the dynamic height is summed to the 2000 decibar level, this gives an error of 1.4 dynamic centimeters. Conversely, when summing to this level, to justify giving the dynamic height to 1/10th of a dynamic centimeter it requires that the salinity titration be accurate to $\pm 0.0003°/_{oo}$ Cl. while to justify the second decimal point requires an accuracy of $\pm 0.00003°/_{oo}$ Cl. It is safe to say that such accuracy is never approximated to in routine laboratory work. A good laboratory analyst, using the standard salinity method, probably never reaches a better figure than $\pm 0.003°/_{oo}$ Cl. which entails an error of about one dynamic centimeter. Though this accuracy is seen to be far less than would warrant the usual pseudo accuracy of the calculation, the accuracy of individual titrations at a station is usually much less, an error of $\pm 0.015°/_{oo}$ Cl. being usually tolerated. Such an error would, for 100 decibar interval, correspond to an error of 0.2 dynamic centimeters. In the deeper water, where the intervals between samples are often as great as 400 meters, this would correspond to an error of 0.8 dynamic centimeters. Further errors arise in taking off the values of salinity and temperature from the depth curves. The straight line as opposed to the smoothed curve method gives appreciably different results, while two equally reasonable drawings of the same smoothed curve may involve a difference, in 2000 decibars, of as much as 1.0 dynamic centimeters. In some cases these errors may compensate for one another but quite as often they will be, to some extent, additive. In view of this it does not seem rash to assume that the dynamic heights computed to the 2000 decibar level are, even in careful work, often in error by as much as 2 dynamic centimeters, while 100 decibar units may be in error by as much as 0.25 dynamic centimeters. The first decimal place of dynamic centimeters then, in a computation to any considerable depth, has no significance and an attempt to give the result to the second or third place is misleading and unnecessary.

At "Anchor" stations the usual procedure is to determine the temperatures for all lowerings, while the salinities are determined for but a limited number. From these determinations the salinity-temperature curve is constructed and from this curve, the salinity for the temperatures on the various hauls, deduced. Temperatures and salinities are thus found for standard depths and the dynamic heights calculated, either from the table of Bjerknes (1910) or Sverdrup (1933).

A much shorter procedure is as follows. From the salinity-temperature curve, salinities corresponding to even temperatures are found. Using these values the uncorrected anomaly corresponding to each temperature can be obtained, either directly by the use of Bjerknes' tables (H9, H10, H11), or from Sverdrup's Table I after the corresponding values of σ_t have

been deduced. The result can be expressed as a temperature-uncorrected anomaly curve. The change of salinity at any standard depth is such that the extreme range of the factor $\delta_{s,p}$, is about 0.15 of anomaly. If then it is treated as a constant at any standard depth we are still well within the accuracy of the method. This constant may be combined with the original temperature-anomaly curve or, if preferred, with the values for $\delta_{t,p}$.

The temperature change at some standard depths may, over a 14 day period, be as much as 3.6° C. (Seiwell, unpublished). At most depths, it is

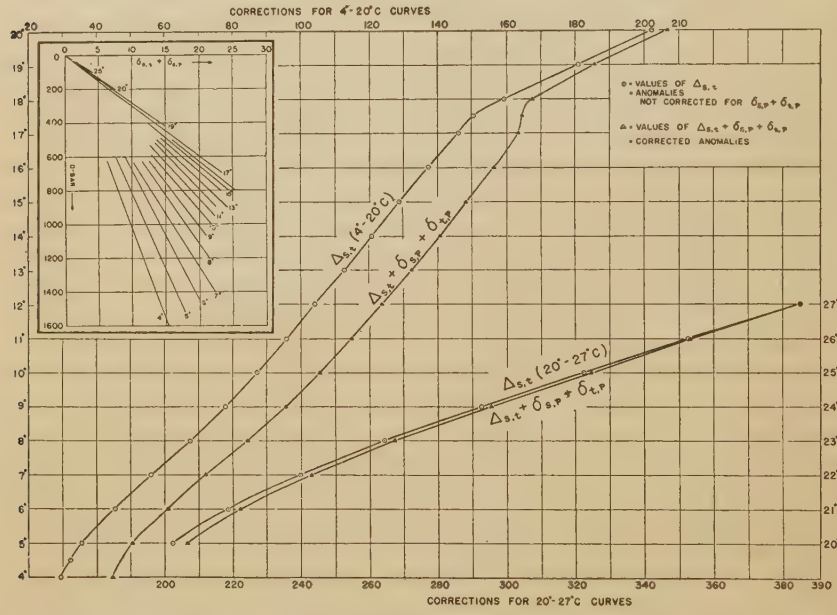
CORRECTIONS FOR 4°-20°C CURVES
CORRECTIONS FOR 20°-27°C CURVES
o = VALUES OF $\Delta_{s,t}$ + ANOMALIES NOT CORRECTED FOR $\delta_{s,p} + \delta_{t,p}$
Δ = VALUES OF $\Delta_{s,t} + \delta_{s,p} + \delta_{t,p}$ + CORRECTED ANOMALIES
$\Delta_{s,t}$ (4°-20°C)
$\Delta_{s,t} + \delta_{s,p} + \delta_{t,p}$
$\Delta_{s,t}$ (20°-27°C)
$\Delta_{s,t} + \delta_{s,p} + \delta_{t,p}$
DECIBARS

Figure 36. Curves for the determination of the Anomaly of Specific Volume from the temperature at "Atlantis" station No. 3183.

considerably less than this. To assume the mean temperature at any standard depth in determining the factor $\delta_{t,p}$ would introduce an error not greater than that already present due to the standard procedure. Further, as the phase of the movement is different at different depths, the errors introduced when summing to, say, 2000 decibars will to some extent cancel out. Thus, for rough work this factor too, could be considered as a constant and combined with the original curve. It would be more correct however, to derive this factor from Bjerknes' tables (H13) or from Sverdrup's tables (6a and 6b). For convenience this correction can be expressed as a graph.

The procedure would then be to draw the temperature-depth curve for the lowering as is always done, and take off temperatures for standard depths. From these values the approximately correct anomaly could be derived directly from a temperature-anomaly curve (in which the factors $\delta_{s,p}$ and $\delta_{t,p}$ are both assumed constant for any given standard depth) or, more accurately, the anomaly, corrected for everything except $\delta_{s,p}$ and $\delta_{t,p}$, could be taken off from a temperature anomaly curve and the factors $\delta_{s,p}$ and $\delta_{t,p}$ determined as already described, from a single graph.

This procedure is much quicker than either of the two standard methods. It does not necessitate taking out salinity values for all lowerings, and it reduces the subsequent corrections, even when the accurate method is used, from two to one. Over Bjerknes' method it has the advantage that it substitutes one reference, or at most two references to curves for reference to 5 sets of tables. By this method the time for this operation can be reduced to about 1/5th of that required for either of the other procedures. In addition, as there are far fewer figures used and fewer references to be made, the chance of error is greatly reduced.

As an example of this method and to test its accuracy, "Atlantis" Station 3183 was examined by both the standard procedures and the method just outlined. The curves used are shown in Fig. 36. Calculating to the 1500 decibar level, for lowerings, the result by the quick method, by which the anomaly is known immediately from the temperature, never differed by more than 0.6 dynamic centimeters from that found by the standard procedure; while when the more accurate procedure, using a specific value for $\delta_{t,p}$, was used the difference did not exceed 0.2 dynamic centimeters. In view of what has already been said as to other sources of error these errors seem to be of no significance.

Of course this method depends upon the constancy of the salinity-temperature correlation. It can therefore be applied whenever this correlation is sufficiently accurate. It is hoped to show elsewhere that this condition holds for the deeper waters around Bermuda for any one month.

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DISTRIBUTION OF DIATOMS IN RELATION TO THE CHARACTER OF WATER MASSES AND CURRENTS OFF SOUTHERN CALIFORNIA IN 1938

By

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INTRODUCTORY REMARKS

In 1938 the "E. W. Scripps" made six cruises at intervals of two months, covering on each cruise the same area off the coast of southern California. The station plan is shown in Figure 37, but not all stations indicated in that

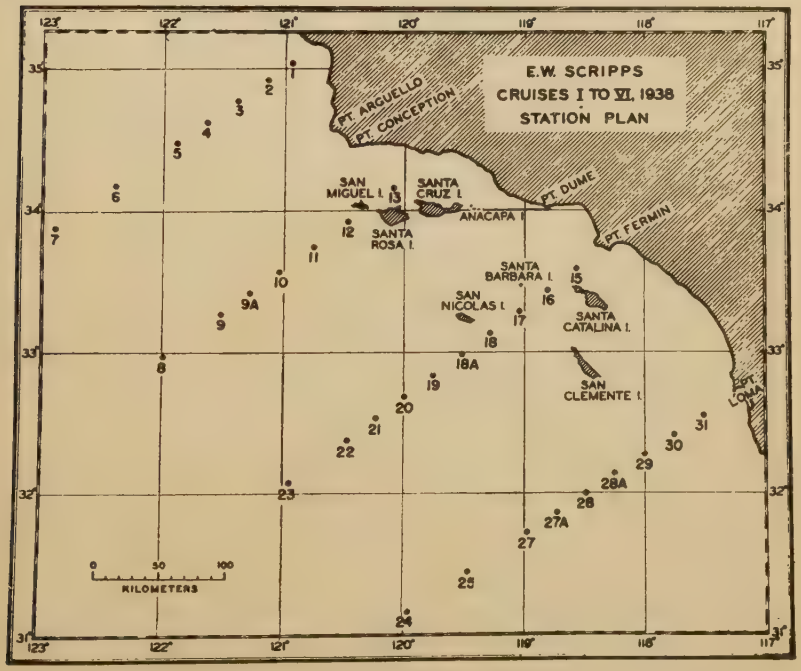

Figure 37. Station plan of the "E. W. Scripps" cruises I to VI, 1938.

* Contributions from the Scripps Institution of Oceanography. New Series, No. 69.

figure could be occupied on each cruise owing to unfavorable weather conditions and the short time available for completion of the work. On all cruises observations of temperature, salinity, and oxygen were made between the surface and a depth of 600 meters. The observations were limited to 600 meters because work in 1937 had clearly shown that within this area conspicuous horizontal differences in temperature and salinity were found above 500 meters only, and when carrying out dynamic computations the 500-decibar surface could be used as the reference level. Collections for phytoplankton were made at most stations by taking samples at intervals of 10 meters between the surface and 60 meters, except that on Cruise III samples were taken from 70 meters instead of at 40 and 60 meters. The water samples were obtained by means of the Allen closing bottle which has a capacity of 5 liters, and were filtered through a net of number 25 silk bolting cloth. Later on the diatoms were counted and recorded as number of diatoms per liter. In this paper the relation between the water masses and the character of the currents and the number of diatoms present will be dealt with.

CHARACTER OF SURFACE WATERS

When discussing similar hydrographic data from three cruises in 1937 Sverdrup and Fleming (in press) were able to show that in the spring and early summer three types of surface water were present, (1) inshore surface water, (2) offshore surface water, and (3) mixed surface water. Under "surface" water the water down to a depth of about 100 meters is understood.

In spring and early summer the inshore surface water represented water which had recently been drawn to the surface by processes of up-welling and which was, therefore, of low temperature and of high salinity. In most localities a warming and stirring had taken place near the surface and a thin convection layer was present below which a sharp decrease of the temperature took place. The region of sharp decrease is called the thermocline, and in inshore water the depth to the thermocline is small.

The offshore surface water was, on the other hand, characterized by a thick convection layer of relatively high temperature and low salinity and by a great depth to the thermocline.

The surface water of a mixed type had a salinity which was intermediate between those of the inshore and offshore waters and often had high temperatures near the surface and a relatively thin convection layer.

These three types of surface waters were encountered on all cruises in 1938, but it appeared that the name "offshore" surface water is somewhat misleading. The name was chosen because in spring and early summer, when the 1937 cruises were made, water with a thick convection layer was found in the offshore areas only, but in 1938 water of similar characteristics,

except that the temperature was lower, was present near the coast in winter. It might be more correct to call the two types "new" and "old" surface water because a thin convection layer is characteristic of water which has been recently drawn to the surface, whereas a thick convection layer is characteristic of water which has spent a long time as surface water. We shall retain the terms, however, particularly because the name "inshore" surface water appears to be very appropriate for reasons which will presently be explained.

RELATION BETWEEN CHARACTER OF SURFACE WATER AND CURRENTS

Owing to its lower temperature and greater salinity the inshore surface water has a greater density than the offshore water. Within areas of

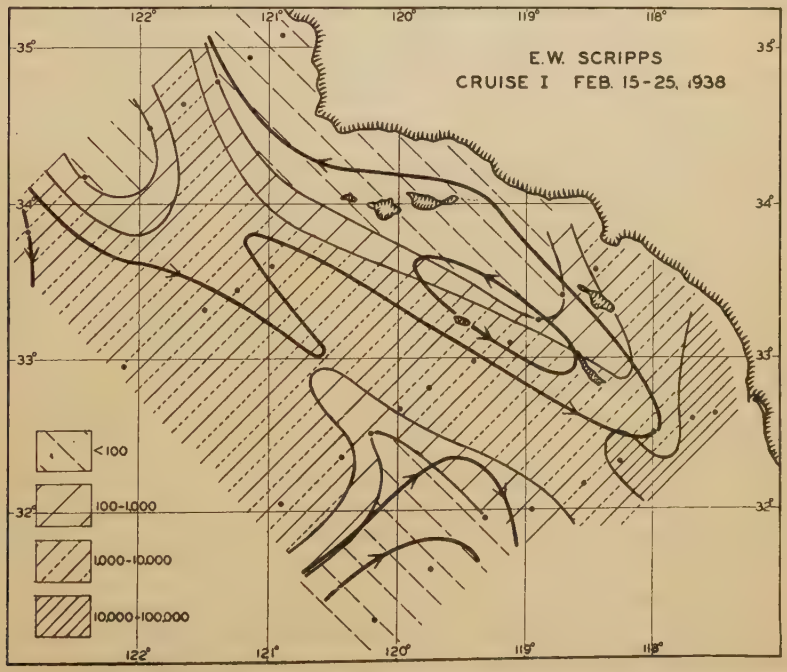

Figure 38. "E. W. Scripps," Cruise I, 1938. Character of currents, indicated by heavy lines with arrows, and distribution of diatoms, indicated by hatching.

inshore water the distances between isobaric surfaces will therefore be smaller, and on charts of relative dynamic topography of the surface the areas of inshore water will appear as "Lows" and the areas of offshore

water as "Highs." If, as is usual, the contour lines of the surface are interpreted as approximate stream lines, an isolated area of inshore water will appear as a cyclonic eddy and one of offshore water as an anticyclonic eddy. Such eddies are present on all of our charts and it is particularly interesting to observe that eddies of inshore water are often found at great distances from the coast. That the water of these eddies actually is of

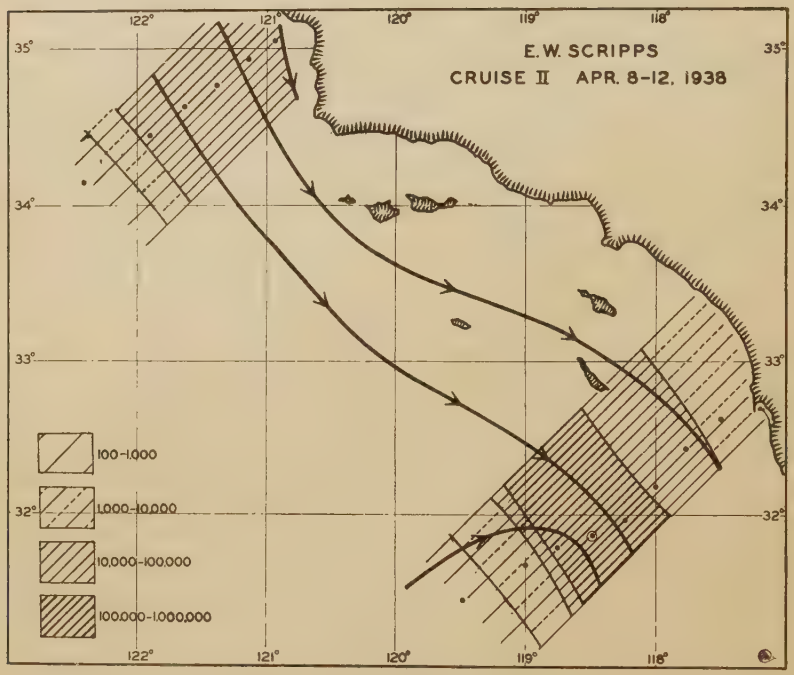

Figure 39. "E. W. Scripps," Cruise II, 1938. Character of currents, indicated by heavy lines with arrows, and distribution of diatoms, indicated by hatching.

inshore character has been confirmed by M. W. Johnson's study (1939) of the distribution of crab larvae on the cruises in August, October, and December, 1938. Larvae of the common sand crab, *Emerita*, and other unidentified crab larvae were found at distances up to 150 miles from the coast, and with one exception all of those found at some distance from the coast occured in waters which, on the basis of their physical-chemical characteristics, had been classified as inshore water. The presence of crab larvae in these waters represents independent evidence of the correctness of the classification.

THE CHARACTER OF THE CURRENTS

The currents are quite complicated, but a certain annual cycle in the pattern of flow is revealed by a study of Figures 38 to 43. In these figures attention will first be drawn to the heavy lines provided with arrows, which can be interpreted as approximate stream lines at the time of the cruise, although they actually represent lines of equal dynamic anomaly of the

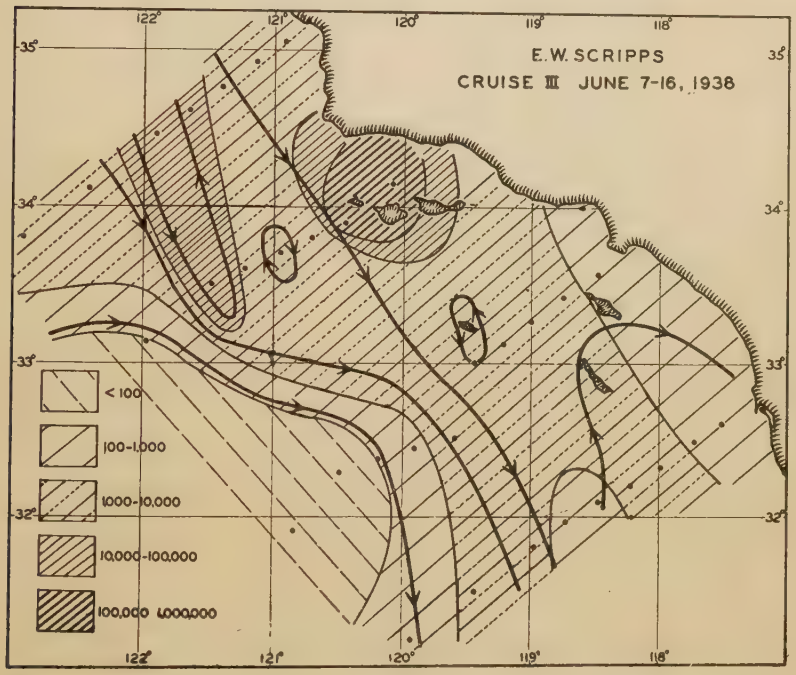

Figure 40. "E. W. Scripps," Cruise III, 1938. Character of currents, indicated by heavy lines with arrows, and distribution of diatoms, indicated by hatching.

surface above the 500-decibar surface. On Cruise I in February there was an inshore flow towards the northwest past Point Conception, a cyclonic eddy was located between San Clemente and San Nicolas Island, and an anticyclonic eddy was present in the southern part of the area. The inshore flow has been called the California Counter Current and is present during a considerable part of the year but it disappears during the period of upwelling.

Cruise II in April was very incomplete owing to unfavorable weather, but the few available data indicate that upwelling had been going on for some

time and that, consequently, the Counter Current had disappeared and had been replaced by a more or less regular flow towards the southeast.

Prior to Cruise III in June upwelling had continued and as a consequence the light surface water had been transported to a considerable distance from the coast. The boundary between the inshore upwelled water and the offshore surface water was characterized by a swift current towards the

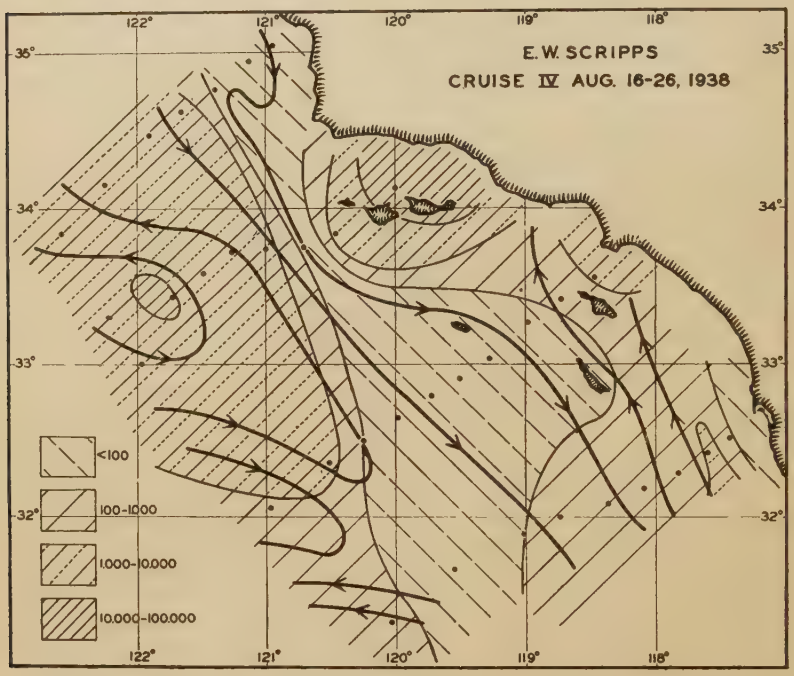

Figure 41. "E. W. Scripps," Cruise IV, 1938. Character of currents, indicated by heavy lines with arrows, and distribution of diatoms, indicated by hatching.

southeast. The Counter Current appeared again in the southeastern portion of the area.

On Cruise IV in August the strong flow to the southeast in the offshore area appeared to have broken down in a number of eddies. The cyclonic eddy located off the Channel Islands was of inshore origin because the water in this eddy showed the characteristics of upwelled water, whereas the anticylonic eddy in the southern corner of the area was formed by offshore water. The Counter Current was developed in the southeastern part only.

On Cruise V at the end of October and the beginning of November, the offshore area was again characterized by two eddies, one cyclonic containing inshore water and one anticyclonic containing offshore water. The Counter Current was still rudimentary.

On Cruise VI in December conditions were encountered which showed considerable similarity to those met with in February. The Counter Current

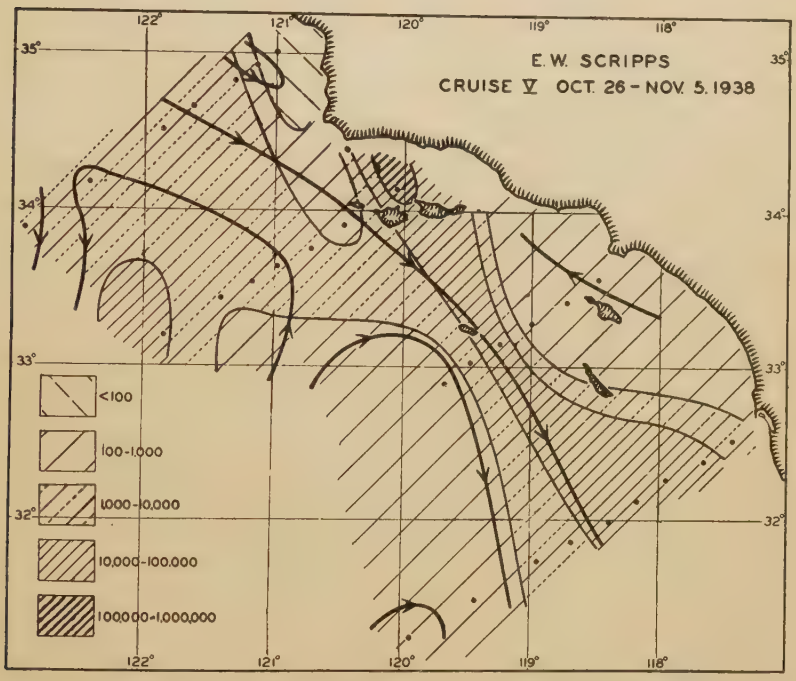

Figure 42. "E. W. Scripps," Cruise V, 1938. Character of currents, indicated by heavy lines with arrows, and distribution of diatoms, indicated by hatching.

was again fully developed, and outside of the Counter Current a large cyclonic eddy was present. In the southern corner of the area an extensive anticyclonic eddy dominated.

Summarizing these features it can be stated that close to the coast the California Counter Current is more or less prevailing except in the period when intensive upwelling takes place. At greater distances from the coast a distinct flow to the southeast is found only during the period of upwelling in the spring, and during the greater part of the year the offshore area is characterized by eddies which rotate cyclonically or anticyclonically, the

former containing inshore water and the latter containing water of offshore characteristics.

DISTRIBUTION OF DIATOMS

In Figures 38 to 43 the average number of diatoms per liter between the surface and 60 or 70 meters has been indicated by hatching. It should be

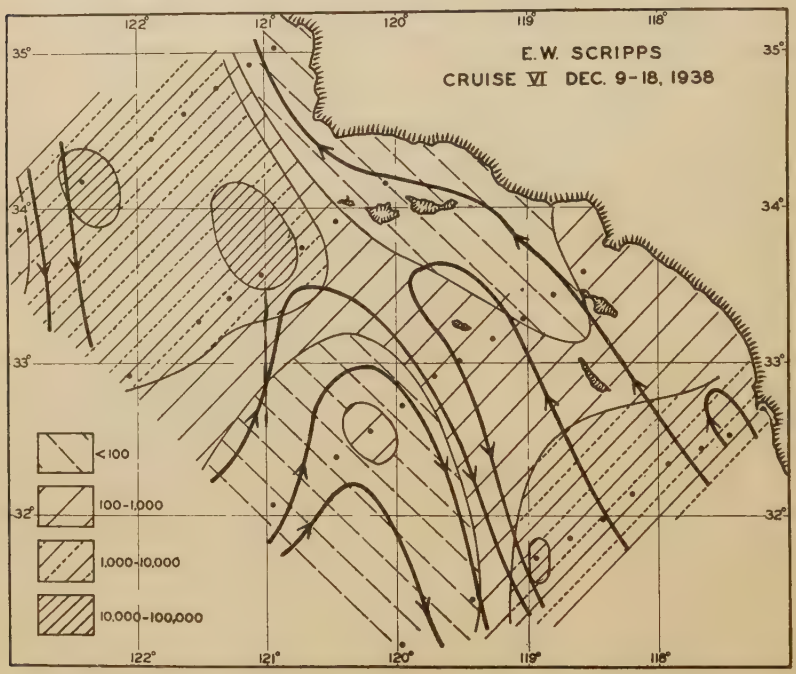

Figure 43. "E. W. Scripps," Cruise VI, 1938. Character of currents, indicated by heavy lines with arrows, and distribution of diatoms, indicated by hatching.

observed, in the first place, that neighboring stations often show similar conditions. The stations with numerous or few diatoms are not distributed at random but a certain pattern of distribution appears from which it may be concluded that the method of sampling has been adequate and that the distribution of the diatoms is approximately correctly represented. This conclusion is also confirmed by the fact that if numerous diatoms were found at one level at any station the numbers at the other levels of the same station were also high. Thus, a certain system prevails both in horizontal and vertical directions and a closer inspection of the different charts bears

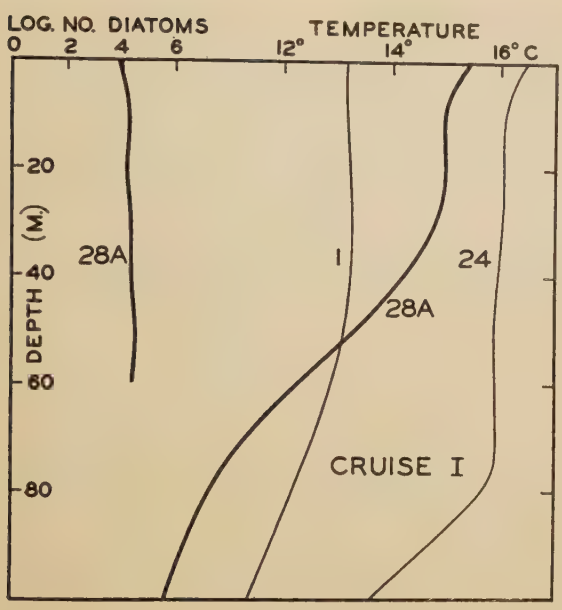

Figure 44. "E. W. Scripps," Cruise I, 1938. Vertical distribution of temperature at Stations 1 and 24 (few diatoms) and at Station 28A. Vertical distribution of diatoms at Station 28A.

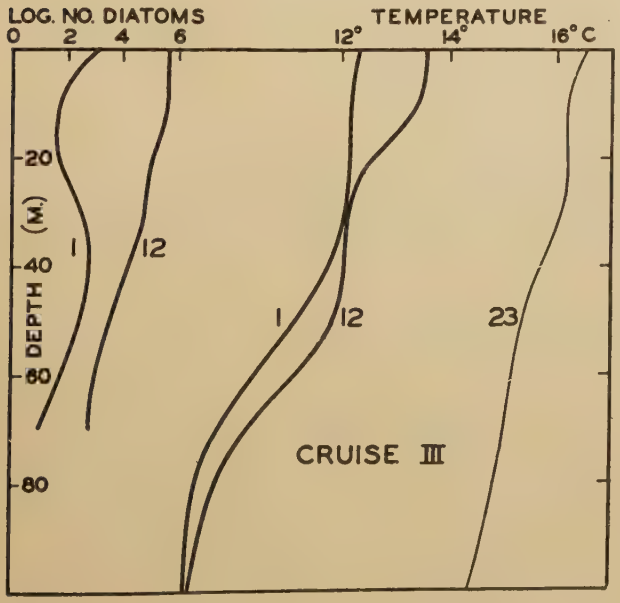

Figure 45. "E. W. Scripps," Cruise III, 1938. Vertical distribution of temperature at Station 23 (few diatoms) and at Stations 1 and 12. Vertical distribution of diatoms at Stations 1 and 12.

out that this system is related to the character of the surface waters and the currents.

On Cruise I in February few diatoms were found in the Counter Current which was characterized by a thick convection layer and very few in the conspicuous offshore water eddy in the southern corner which also was characterized by a thick convection layer. Diatoms were present in moderate numbers over large areas within which the waters were all more or less

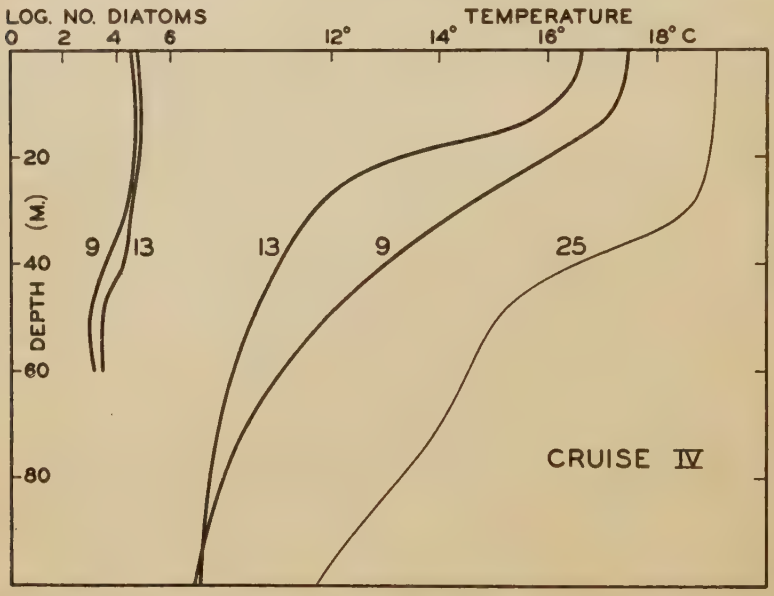

Figure 46. "E. W. Scripps," Cruise IV, 1938. Vertical distribution of temperature at Station 25 (few diatoms) and at Stations 9 and 13. Vertical distribution of diatoms at Stations 9 and 13.

inshore in character and with relatively thin convection layers. Figure 44 has been prepared in order further to emphasize this relationship. In this figure are shown the vertical distribution of temperature between the surface and 100 meters at Stations 1 (in the Counter Current), 24 (in the offshore water eddy) and 28A (at the southern end of the inshore water eddy). At Stations 1 and 24 the number of diatoms was less than 100 cells per liter but Station 28A showed the greatest abundance with an average of more than 10,000 cells per liter. The convection layer was thick at Stations 1 and 24 and thin at Station 28A. The vertical distribution of diatoms at Station 28A is also entered and appears to be nearly independent of depth down to 60 meters.

On Cruise II much larger numbers of diatoms were present but most available observations were made in water of inshore character, for which reason no great contrasts appear.

On Cruise III in June the big eddy of offshore water in the southwestern portion of the area was lacking in diatoms, but in the upwelled water which extended to considerable distances from the coast large numbers were present. The greatest abundances were encountered near the Channel

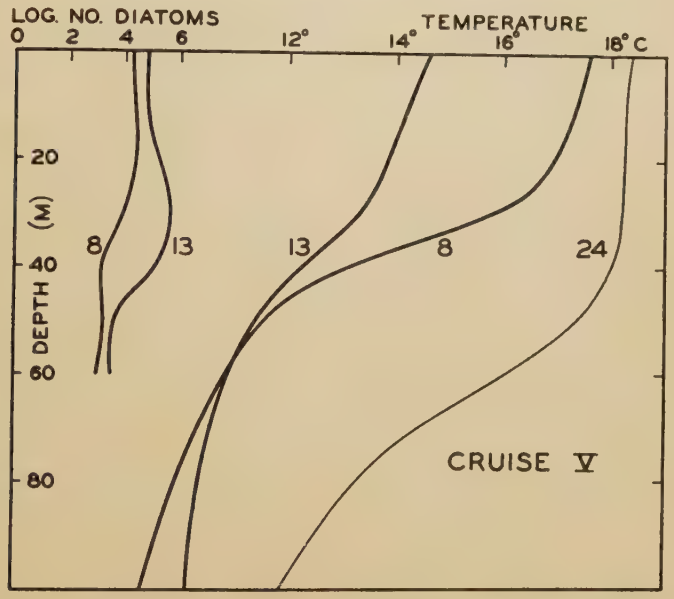

Figure 47. "E. W. Scripps," Cruise V, 1938. Vertical distribution of temperature at Station 24 (few diatoms) and at Stations 8 and 13. Vertical distribution of diatoms at Stations 8 and 13.

Islands and within a cyclonic eddy to the west of Point Conception. The distribution of diatoms was again related to the thickness of the convection layer. Figure 45 shows the vertical distribution of temperature at Station 23 located in the offshore water and at Stations 1 and 12 near the coast in the region of upwelling. At the two latter stations the convection layer was thin, but at Station 23 the upper layer of high temperature was more than 100 meters thick. At Station 23 the number of diatoms was less than 100 cells per liter but at Stations 1 and 12 numerous diatoms were found. According to the curves showing the vertical distribution of diatoms at Stations 1 and 12 the greater number was found above the thermocline.

On Cruise IV there was less agreement between the distribution of diatoms and the pattern of flow, particularly within the central part of the area where, according to the results from the preceding cruise, one should have expected a considerable population but where no diatoms were present. A great abundance was found on this cruise, however, at the center of a big eddy of inshore water to the southwest of Point Conception. The waters of this eddy contained, on the whole, considerable populations of diatoms and the greatest numbers, averaging more than 10,000 cells per liter, were

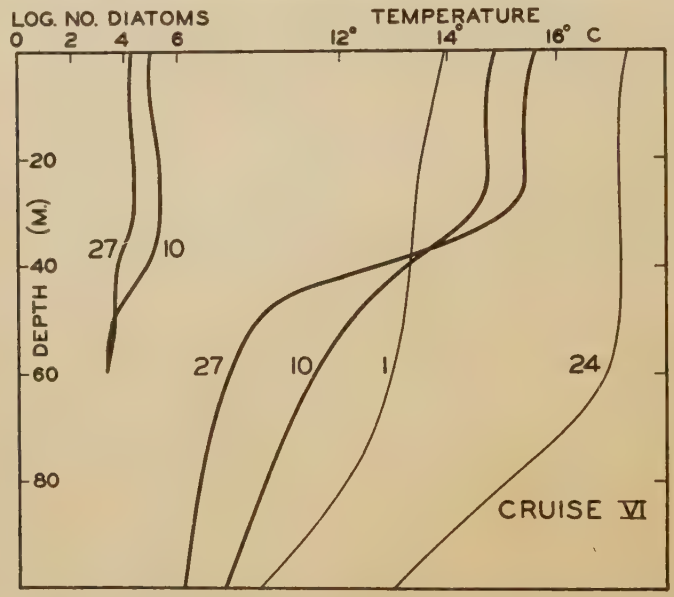

Figure 48. "E. W. Scripps," Cruise VI, 1938. Vertical distribution of temperature at Stations 1 and 24 (few diatoms) and at Stations 10 and 27. Vertical distribution of diatoms at Stations 10 and 27.

found right at the center of the eddy. In the Santa Barbara Channel the abundance was also great, but the eddy of offshore water in the southern corner showed very few diatoms. The relation between the depth to the thermocline and the number of diatoms is illustrated in Figure 46 in which are shown curves of vertical temperature distribution at Stations 25 (in the offshore water eddy), 13 (in the Santa Barbara Channel) and 9 (in the inshore water eddy). At the two latter stations the depth to the thermocline was small and numerous diatoms were present, as shown by the curves to the left, but at Station 25 the depth to the thermocline was considerably greater and diatoms were lacking. At Stations 9 and 13 the greater abundance again was found above or in the thermocline.

On Cruise V the agreement between the currents and the distribution of diatoms was again good. The inshore counter current had few diatoms but large numbers were found in the flow to the south at a short distance from the coast. The most conspicuous feature was, however, that the cyclonic eddy of inshore water in the northern part of the area showed a great abundance of diatoms, particularly near the center, whereas the anticyclonic eddy of offshore water in the southern portion had few diatoms. Figure 47 demonstrates the relation between the depth of the thermocline and the number of diatoms at a few selected stations. At Station 24 in the eddy of offshore water the depth to the thermocline was great and very few diatoms were found, but at Station 13 in the Santa Barbara Channel and at Station 8 at the center of the eddy of inshore water the depth to the thermocline was small and both stations showed large numbers of diatoms, as evident from the curves to the left. Again the greater number was found above or in the thermocline.

On Cruise VI the pattern of flow was similar to that on Cruise I and the distribution of diatoms also shows considerable similarity. The counter current contained very few diatoms except in the southern part, exactly as was the case in February. Similarly, the offshore eddy in the southern portion was lacking in diatoms but otherwise moderate numbers of diatoms were found over considerable areas. Figure 48 shows the vertical temperature distribution at a few selected stations. At Station 1 within the counter current and at Station 24 in the eddy of offshore water the depth to the thermocline was great and no diatoms were present. At station 10 off the Channel Islands and at Station 27 in the southern part of the inshore water eddy the depth to the thermocline was small and numerous diatoms were found, particularly above and in the thermocline.

CONCLUSIONS

It is evident from this examination that generally the eddies of offshore water contain few diatoms, whereas eddies of inshore water may contain considerable numbers. It is also evident that the counter current is, on the whole, lacking in diatoms, whereas the southeast-flowing upwelled water which is characteristically present in spring contains numerous diatoms.

The relationships which have been shown to exist between the depth to the thermocline and the number of diatoms can be interpreted as showing that the "age" of the surface water is of great importance. It was pointed out that a thick convection layer and a great depth to the thermocline is found within waters which have existed as surface waters for a long time, whereas a thin convection layer and a small depth to the thermocline indicate that ascending motion has taken place recently and that the water in question has not yet spent a long time as surface water. Without ex-

ception, few diatoms were found within water masses which had existed as surface waters for a long time and large populations of diatoms were found only in water masses which had spent relatively a short time as surface waters. On the other hand, water which had recently been drawn to the surface or was of mixed type did not always contain many diatoms. Factors must therefore exist which limit the size of the population in areas where the character of the waters appears favorable for large numbers of diatoms. These factors are probably of combined biological and chemical nature, meaning that the diatoms may not have had time to develop or may have been removed by grazers after or prior to a depletion of necessary nutrient salts. The conspicuous absence of diatoms in the offshore water is probably due to depletion of the nutrient substances and removal by grazers.

The important conclusion is that a definite relationship exists between the character of the surface water and the pattern of flow on the one hand and the number of diatoms on the other hand. It is hoped that future studies may help to explain this relationship.

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PLANKTON STUDIES. II. THE WESTERN NORTH ATLANTIC, MAY–JUNE, 1939*

By

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The results of the first paper of this series, a study of the plankton in a tropical shallow water region in the Gulf of Mexico, suggested the desirability of extending the observations to more typically oceanic areas in order to analyze productivity factors in relation to the depth of water and to attempt to estimate the relative productivity of northern and southern seas. Opportunity for such an investigation was obtained during a cruise of the "Atlantis" from the northern coast of Cuba to Woods Hole. Eighteen stations were established during the cruise, and measurements were made at each station of temperature, oxygen, phosphate, nitrate, and total plant pigments from the surface to the approximate limit of the occurrence of phytoplankton. In the surface waters of all stations the chlorophyll content was also determined, and experimental measurements were made of the oxygen and nitrate production and consumption in light and dark bottles. Finally, at five of the stations, quantitative collections of zooplankton were made with Clarke plankton samplers.

I am greatly indebted to the Woods Hole Oceanographic Institution for providing me with the facilities for this work. I should like also to thank Mr. Albert E. Parr and Mr. G. Evelyn Hutchinson for examining and criticizing the manuscript, Dr. George L. Clarke for providing me with plankton samplers, and Mr. Alfred Woodcock, Dr. Henry Mahncke, and Mr. Dean F. Bumpus for help in the collection of materials.

METHODS

The methods used for the determination of total plant pigments, chlorophyll, and oxygen were the same as in the first paper of this series. Nitrates were measured by means of the diphenylbenzidine method of Atkins (1932). In testing this method it was found that analytical errors could be reduced by doubling the quantity of sea water and reagents used in order to minimize the error involved in measuring out small volumes of fluid. Otherwise the method used was exactly as described by Atkins.

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Work by Cooper (1938) on the salt error in determinations of phosphate makes it necessary to specify the exact conditions of the test. The original Atkins-Deniges method was used, with 2 ml. of molybdate reagent per 100 ml. of water, and the comparison was made in a Bausch and Lomb colorimeter with 100 mm. cups. The salt error unfortunately was not determined for each analysis, but measurements made later on three samples of surface water collected during the cruise gave an average of 1.39. Since this is somewhat higher than the usual values, and moreover since the reagents were contaminated (an amount equivalent in the ordinary conditions of the test to a concentration of about 0.15 mg. atoms of P per m^3 in sea water), which magnified the error in the determination of small quantities of phosphate, the values given should be regarded only as approximate.

The experiments were conducted in the following way: 250 ml. bottles were filled with surface water in the same manner as for routine oxygen tests. The bottles were exposed for a period of three days. When the vessel was in port, the bottles were hung over the side at a depth of one meter in a position where they would receive direct sunlight all day. This included the first three stations and parts of six others. At sea it was necessary to adopt a makeshift procedure in which the bottles were suspended in a tub on deck, and the water in the tub, surrounding the bottles, was changed frequently in order to maintain a normal temperature. Duplicate experiments performed during the early part of the cruise showed no significant difference in the results of the two methods. At the end of the period of exposure, the bottles were shaken thoroughly before being unstoppered. One milliliter of water was then removed for a nitrate test, and the Winkler reagents were immediately added to the remainder.

LOCATION OF STATIONS

The positions of the stations are shown in Figure 49. Eight of the Stations, 3491 to 3512 inclusive and 3523, were in the Gulf stream. Five of them, 3513 to 3520, were in the Sargasso Sea. All these, and in addition Station 3486, off the coast of Cuba to the east of the Florida Straits, may be regarded as tropical waters, in the sense that they were in regions of high and relatively constant temperature, although the conditions were different from what is found in equatorial waters. The three northernmost stations were typical North Atlantic slope waters, and the remaining one, 3528, apparently was transitional, but was more nearly characteristic of northern than of tropical water.

TEMPERATURE AND LIGHT

The surface temperature in the southern areas varied from 22° to 27°, the higher temperatures being found in the Gulf Stream and the Florida

Straits and the lower ones in the Sargasso Sea. In the latter there was a decrease of three or four degrees in the first hundred meters and little further change in the next three hundred. In the Gulf Stream, on the other

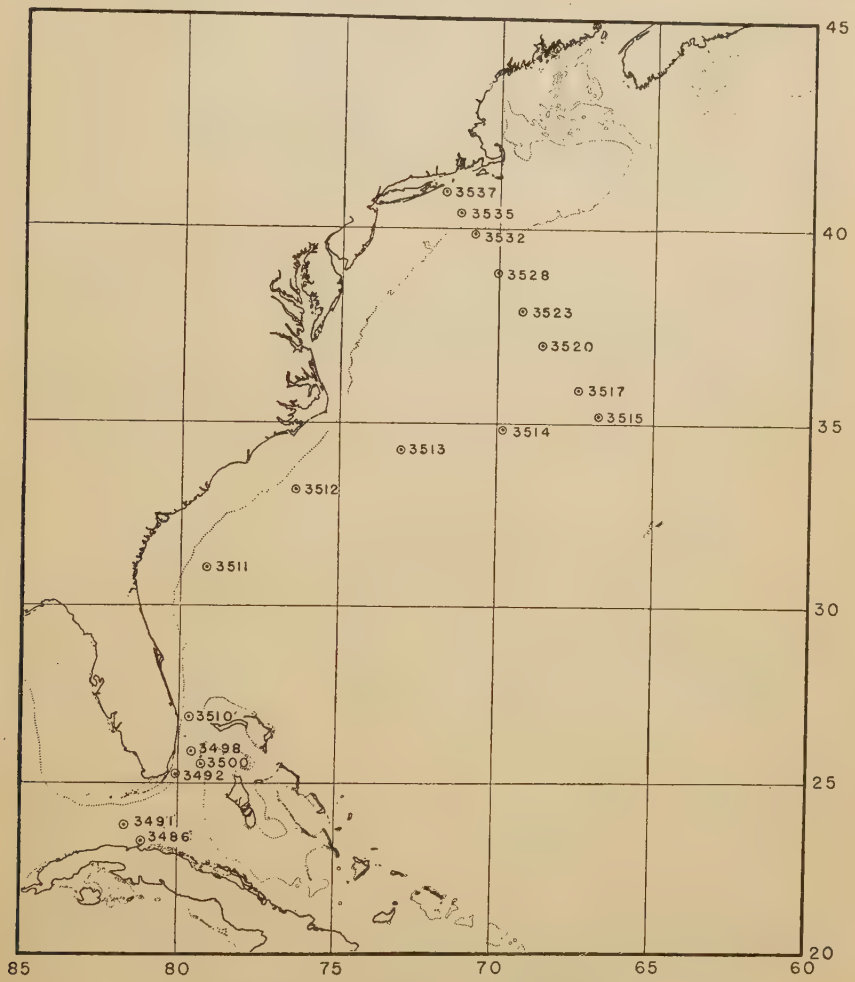

Figure 49. Station numbers and positions.

hand, there was a fairly distinct thermocline lying somewhere between one hundred and three hundred meters below the surface.

At the three northernmost stations, the surface temperature was from 10.63° to 12.52°, and at Station 3528, designated above as transitional, it

was 19.67°. The thermocline probably lay at about 25 m. throughout most of this area.

The normal radiation for the region studied was estimated roughly by interpolation of data given by Kimball (1928). The normal total radiation is approximately the same for the entire region during May and early June, the greater light intensity in the south being compensated by the longer day in the north, and the total estimated range being from 456 to 462 g. cal. per cm^2 per day. Therefore, in comparing plankton conditions at different latitudes it is unlikely that variations can be ascribed to differences in radiation, unless the season was quite abnormal.

THE STANDING CROP OF PHYTOPLANKTON

The collection of materials for analyses of plant pigments and chlorophyll was made by filtering two or three liters of water through a Whatman No. 2 filter paper. No analyses were made of net plankton.

The analyses of surface phytoplankton in the southern waters, summarized in Table I, are slightly higher but of the same order of magnitude as the shallow water determinations reported in the previous paper (average

TABLE I

Plant Pigments and Chlorophyll in the Surface Waters

	Tropical Waters (14 analyses)	*Northern Waters (4 analyses)*	*All Analyses*
Plant pigments (Harvey units per m^3)			
Maximum	3500	8300	8300
Minimum	600	1700	600
Mean	1300	4100	1900
Chlorophyll (Mgs. per m^3)			
Maximum	2.5	3.6	3.6
Minimum	0.4	1.4	0.4
Mean	1.0	2.1	1.2

1300 Harvey units per m^3 in the present work, and in the Tortugas region 924 units). The mean of the five stations in the very deep water of the Sargasso Sea is slightly less, 860 units.

The maximum quantity of phytoplankton probably occurs somewhere between the surface and 100 m. In all but two of the analyses of tropical waters, the quantity of plant pigments was greater at 100 m. than at the surface. The maximum depth of occurrence is sometimes 400 m. or more, three out of five analyses at that depth yielding slight but detectable quantities of plant pigments.

The four analyses of northern surface waters yielded a mean of 4100 Harvey units of pigments per m^3 and 2.1 mgs. of chlorophyll. The plant pigments were three times as high as in the southern waters, and the chlorophyll was twice as high. The vertical distribution of plant pigments at the two northern deep water stations is shown in Figure 50, together with the mean distribution in all the southern waters examined. It is evident from

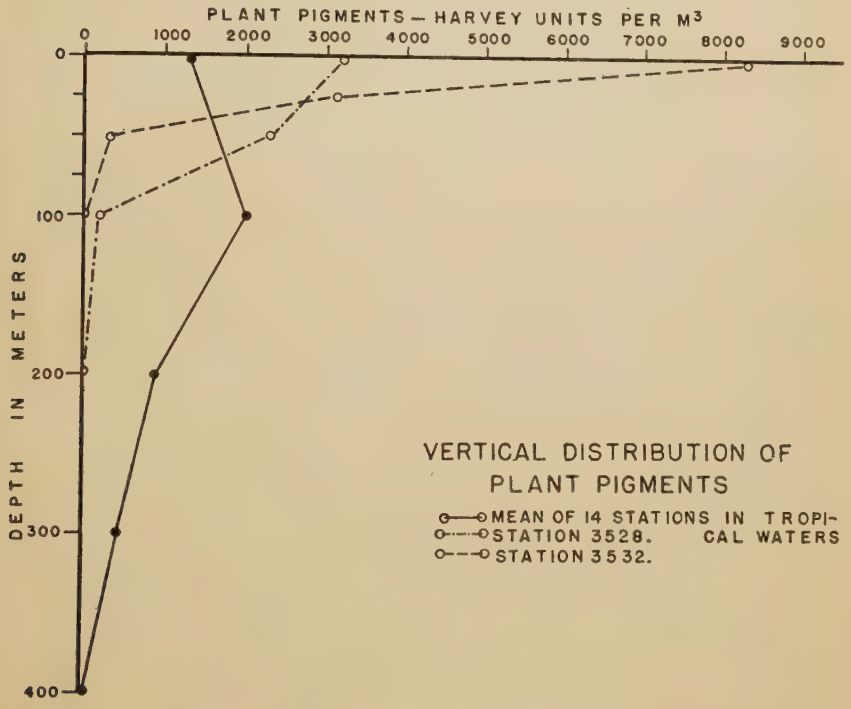

Figure 50. Vertical distribution of plant pigments.

the figure that not only is the northern phytoplankton concentrated in a much shallower stratum of water, but also that the total quantity of plant pigments is considerably greater in the south. The plant pigments per unit area were determined roughly by interpolation between successive levels, with the following results: mean of the four analyses of northern waters—143,000 Harvey units per m^2; mean of the two northern deep water stations—197,000 units; mean of the fourteen southern stations—345,000 units. Even the most completely oceanic stations, the five analyses in the Sargasso Sea, showed a larger standing crop than the northern stations, the

mean being 310,000 units per m^2 and the smallest observed value 235,000 units.

This result appears rather anomalous in view of the prevalent belief that the quantity of plankton in tropical waters is much smaller than that in temperate regions. Lohmann's data on centrifuge plankton (1920), conveniently summarized by Harvey (1928) in tabular form, show a mean annual crop of 500 to 600 cells per liter in the upper 400 m. in latitudes 0° to 30° N, 2000 cells per liter from 30° to 40°, and 6000 cells from 40° to 50°. Differences in the net plankton are still more marked.

It should be pointed out that the northern waters were approaching summer conditions at the time the present analyses were made. A study of the seasonal cycle, including the spring and autumn blooms, would probably give a higher average for the northern waters. Nevertheless, the two seasonal studies that are available for direct comparison do not change the general picture. In the English Channel in 1934 (cf. Harvey, Cooper, Lebour, and Russell, 1935), the mean standing crop during the spring months was 1800 units per m^3 in the upper 45 m., or 81,000 units per m^2, and the largest observed crop was about 160,000 units. Thus not only was the spring bloom considerably smaller than the average obtained for tropical waters when calculated on an absolute areal basis, but also the mean crop per unit volume was only 1.4 times as large, and the mean for the entire year was slightly smaller.

In a study of Long Island Sound, the mean of sixty chlorophyll analyses during the period from September 2, 1938 to July 28, 1939 was 18.3 mgs. per m^3 at the surface and about 370 mgs. per m^2. The chlorophyll at the fourteen stations in tropical waters, estimated on the basis of the chlorophyll-plant pigment ratio at the surface, was probably about 270 mgs. per m^2, and thus was only slightly less than the crop in Long Island Sound.

While the data presented here are hardly sufficient to permit definite conclusions, it is evident that the generalizations that have previously been made about the regional aspects of plankton and productivity are open to suspicion. More detailed work is needed, for the discrepancies noted here might easily be accounted for on the basis of differences in nutrient supply dependent on seasonal and local variations in physical conditions.

NUTRIENTS

The distribution of nitrate and phosphate is summarized in Figure 51. The vertical distribution of nitrate shows a close inverse relation with the quantity of plant pigments. The minimum is at 100 m. in the southern waters and at the surface in the north, where the maximum quantities of phytoplankton occur, and the increase in nitrate becomes marked at the point of extinction of plant pigments, except in the two northern deep

water stations, where the nitrate remains relatively low at 100 m. in spite of the fact that there is little phytoplankton there. But the slightly higher temperatures at 100 m. indicate that there are disturbing physical factors,

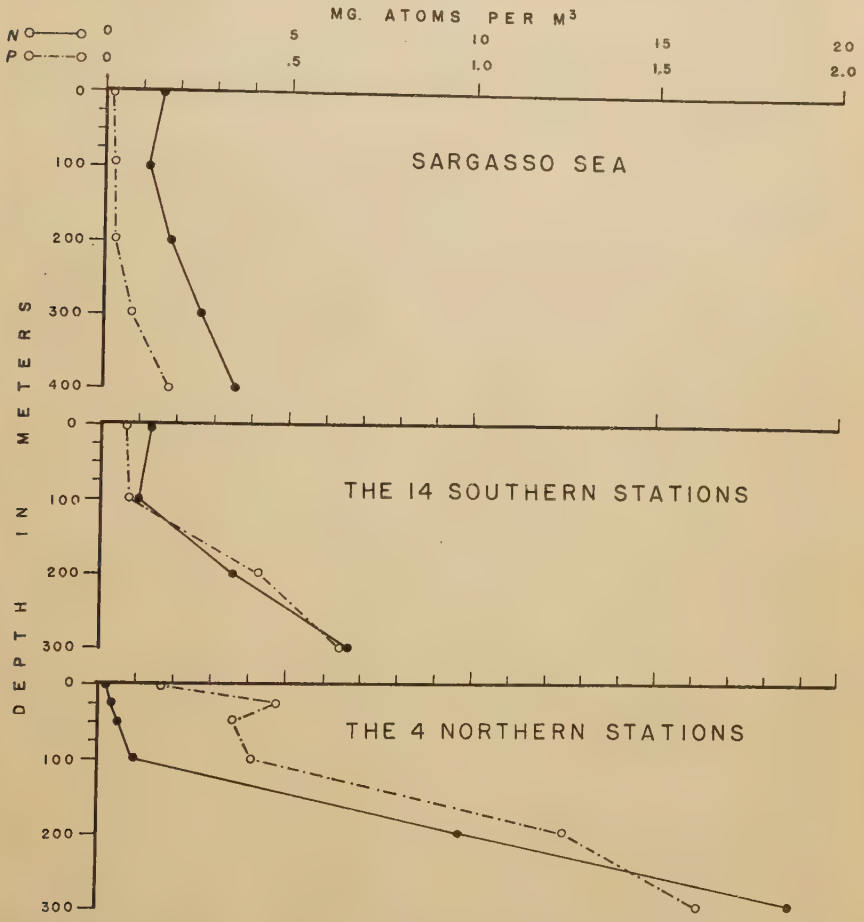

Figure 51. Vertical distribution of nitrate and phosphate.

probably intrusion of southern water. The inverse relation of phosphate with plant pigments is discernible but not particularly striking.

The mean *N:P* ratios of all the southern stations approach the normal value of 15 : 1 (Cooper, 1938). In the Sargasso Sea, however, the phosphates were very low, sometimes undetectable. In the northern waters, on

the other hand, the nitrates were relatively low, with a strong negative anomaly of nearly 14 at the surface, decreasing to 3 at 300 m. This may have been a seasonal phenomenon, due to the fact that the phosphate generally is regenerated more quickly than nitrate after the spring bloom.

OXYGEN AND NITRATE EXPERIMENTS

The experimental values for oxygen and nitrate production and consumption are shown in Table II.

TABLE II

OXYGEN AND NITRATE EXPERIMENTS

Station	*Oxygen production*	*Oxygen consumption*	*Nitrate consumption*	*Decrease in N Light bottle*	*Decrease in N Dark bottle*
3486	.04	.12	.05	.25	.20
3491	.20	.23	.00	.43	.43
3492	.09	.17	.00	.13	.13
3498	.07	.16	.03	−.40	−.43
3500	.03	.03	.00	.20	.20
3510	.21	.18	.00	.03	.03
3511	.15	.09	−.07	−.27	−.20
3512	.07	−.01	−.16	.34	.50
3513	.16	.17	.08	−.49	−.57
3514	.03	.06	.06	.56	.50
3515	.04	.04	.12	.09	−.03
3517	.05	.14	.00	1.00	1.00
3520	.09	.14	.02	.18	.16
3523	.05	.13	.05	.20	.15
3528	.12	.10	−.55	−.60	−.05
3532	.33	.32	.00	.00	.00
3535	.12	.14	1.10	.15	−.95
3537	.15	.05	−.05	.05	.10

Oxygen production and consumption recorded as mgs. per liter per day; nitrate as mg. atoms of *N* per m^3 per day.

The mean oxygen production—the difference between the oxygen content of light and dark bottles at the end of the experiment—was 0.111 mg. per liter per day. At the four stations in northern waters the mean was 0.180 mg.; in the southern waters it was 0.091 mg. Thus the ratio for oxygen production in the two areas is about the same as the chlorophyll ratio.

The mean of all the analyses of the Tortugas region, described in the first paper of this series, was 0.187 mg. per liter per day, and the average for Station 2, which gave more reliable results, was 0.131 mg. This suggests that the production per unit volume at the surface is somewhat

greater in the tropical shallows than in areas of greater depth, but the difference is not very marked. It is apparently considerably greater in northern shallows. Gran (1927) estimated that the mean production in the coastal waters off Bergen was 0.37 mg. per liter per day during the spring bloom of 1922, and Marshall and Orr obtained a value of 0.43 mg. in Loch Striven in April, 1926. The mean of sixty analyses in Long Island Sound between September, 1938, and July, 1939, was 0.461 mg. per liter per day.

Unfortunate circumstances prevented attempts to measure oxygen production throughout the entire euphotic zone. But in view of the scarcity of evidence on oceanic plankton production, it seems desirable to attempt a rough estimate of production in the areas examined, even though the error of such an estimate may be rather large.

The curve for oxygen production against depth may be characterized as increasing slightly from the surface to the point of optimum light intensity and then decreasing exponentially to the limit of photosynthetic activity, which is generally located where the light is about 0.5 to 1% of the incident radiation. In northern waters the optimum light intensity is at about 5 m. (Jenkin, 1937, and others). In the Sargasso Sea, Clarke (1936) found that the optimum for a culture of *Nitzschia closterium* was 80 m. The optimum for the normal Sargasso plankton is probably higher, for in the Tortugas region, in which the water is only slightly less transparent (cf. Taylor, 1928, and Darby, Johnson, and Barnes, 1937), it was found to be between 10 and 15 m. The limit of photosynthesis is probably about 50 m. in the northern waters and 150 m. in the south, these figures being in accordance with the data on light penetration and such evidence as is available for photosynthetic activity (Clarke, 1936; Clarke and Oster, 1934).

Curves for the sixteen deep water stations were drawn by extending the known surface value downward (since the real maximum is unknown) to a depth of 5 m. at the northern stations and 15 m. at the southern ones, with an exponential decrease thereafter to 1% of the surface value at 50 and 150 m. respectively. At Station 3537, with a depth of 38 m., the limit was placed at that depth, and at station 3500 the production was assumed to be uniform from surface to bottom (17 m.). The curves were integrated planimetrically, and the mean for the thirteen southern deep water stations was found to be 0.42 mg. of oxygen per cm^2 per day. The average for all the southern stations was 0.39 mg. At Station 3537 the estimated production was 0.16 mg., and the mean for the other three northern stations was 0.25, giving a general average of 0.23 mg. This would be equivalent to a production of 0.142 g. of oxygen per cm^2 per year in the southern waters and 0.084 g. in the north, representing an annual fixation of 0.053 and 0.032 g. of carbon respectively. Although such estimates can be regarded as little better than guesses, it is interesting to note that they are of the same

order of magnitude as the estimate of 0.0278 g. of carbon which Seiwell (1935) obtained by measuring the oxgyen deficit of the western Atlantic between 3° and 13° N.

In comparing the oxygen production of northern and southern waters, the conclusion appears to be about the same as that which was reached in the comparison of the standing crops. The production at the surface is slightly greater in the north, but the euphotic zone is undoubtedly thicker in the south. The total production per unit area was probably somewhat greater in the southern waters during the particular time the analyses were made. Inclusion of bloom periods would lessen the difference, but even with six months of bloom conditions, with values of about 0.4 mg. of oxygen per liter per day, which seem to be normal for temperate regions, the annual production in the northern area probably would not be significantly greater than in the south.

Obviously such estimates cannot be regarded as critical evidence until much more is known about the variations of photosynthetic activity with depth. Nevertheless, the available data tend toward confirmation of Seiwell's contention, in the paper referred to above, that the tropical waters are not relatively unproductive.

The correlation of oxygen production with chlorophyll is .514, and with total plant pigments it is .614. These correlations are statistically significant, and the variations in the standing crop account for about 55% of the variations in the gross production of glucose. None of the other factors examined—temperature, nitrate, or phosphate—appear to be significant, but there are complications in the statistical treatment which make it appear that the result is due not to a lack of relationships but to complex inter-relationships that cannot be evaluated properly at the present time.

The mean oxygen consumption was 0.118 mg. per liter in the tropical waters and 0.152 mg. at the northern stations. The average of all the analyses was 0.126 mg. per liter. Such large values, particularly in the southern waters where the mean consumption was greater than the production, make it appear unlikely that the values have much significance. It is probable that the well known phenomenon of the multiplication of bacteria in stored seawater (ZoBell and Anderson, 1936, and others) causes a consumption of oxygen that is greater than normal. This viewpoint is supported by the fact that the relationship between plant pigments or chlorophyll and oxygen consumption is slight. The regression equation for all the analyses in southern waters, calculated according to the products moments method, is

$$X = 0.0088Y + 107$$

where Y is Harvey units of plant pigments per m^3 and X is milligrams of oxygen consumed per m^3 per day. The equation gives a mean value for

oxygen consumption by phytoplankton of 11 mgs. per day, or 9% of the total. But according to the probable error of the relationship, the constant for Y may have a variation of $\pm$ 0.0064, so that the statistical estimate lies somewhere between 1% and 17% of the total consumption.

When the equation is applied to the entire vertical column, the estimate for total phytoplankton respiration is 0.30 $\pm$ 0.22 mg. per cm^2 per day. This is a maximal value because the equation is not strictly applicable to respiration at the reduced temperatures found in the lower part of the column. Even so, it appears to be somewhat less than the estimate for total production, which was 0.42 mg. A smaller value is to be expected since the production is theoretically equivalent to respiration plus the oxygen equivalent of organic matter lost from the phytoplankton crop (animal consumption, sinking, etc.).

The number of analyses of northern waters is not sufficient for statistical treatment. Nor is it considered valid to attempt an indirect estimate by treating all the data together, because the wide variation of other factors—temperature, animals, and perhaps bacteria—introduce complex interrelationships that cannot be analyzed accurately with the data available.

The nitrates were determined in the experimental bottles because it was believed that they would provide valuable supplementary evidence on plankton growth. Theoretically, the nitrate consumption—i.e., the difference between the nitrate in the light and dark bottles—can be used to measure production in the same way as the oxygen content, although it is a minimal estimate because there are other forms of nitrogen available, and the results of the two determinations are not quite analogous because the nitrate consumption is obviously a measurement of the formation of protein and other nitrogenous substances rather than glucose.

The results of the experiments, however, are difficult to interpret. There was generally a decrease in the light bottles, averaging 0.10 mg. atom per m^3 per day, but in the dark bottles there was also a decrease, amounting to 0.06 mg. atom. The mean difference between the two—the so-called nitrate consumption—was 0.038 mg. atom.

Without determining the cause of the decrease of nitrate in twelve of the eighteen dark bottles, it is impossible to progress very far with the evaluation of the results. If it were caused by bacterial activity, which might be expected to proceed at an equal rate in both light and dark bottles, the value of 0.038 mg. atom would represent the activity of the phytoplankton. If, on the other hand, the decrease were caused by phytoplankton absorption in the dark, which is known to occur in experiments with pure cultures, with the removal of both nitrate (Ketchum, 1939) and phosphate (Harvey, 1933; Ketchum, 1939), the decrease in the light bottle would be a better estimate of the total utilization by phytoplankton, but it would be minimal because it would take no account of normal bacterial regeneration.

Regardless of which estimate is preferred, there appears to be a discrepancy between the results of the nitrate and oxygen experiments. A nitrate consumption of 0.038 to 0.10 mg. atom per m^3 per day would represent a daily plankton production of 7.6 to 20 mgs. of organic matter with a normal nitrogen content of about 7%. With a mean oxygen production of 0.111 mg. per liter per day, 104 mgs. of glucose would be produced per m^3. About ten percent appears to be used up in normal respiratory processes, and the remainder, 94 mgs., is available for transformation into plankton. This would constitute a daily production of 75 mgs. of organic matter with the usual carbon content of about 50%. The phytoplankton production as measured by the nitrate consumption is therefore only 10% to 27% as great as the oxygen production would suggest.

Such a discrepancy might be due to errors in the experimental technique or variations in the factors involved in the estimates. On the other hand, it might be caused by the failure of the phytoplankton to utilize much of the carbon produced, with a resultant accumulation of large stores of foodstuffs. The experimental evidence is not complete enough to throw any light on the matter; however, the work on Long Island Sound, referred to above, is of interest in this respect, for although it neither confirms nor rejects the first possibility, it helps to clarify the second.

In the first place, on numerous occasions a significant increase in chlorophyll has been observed in the dark bottles (this is in accord with the results of Harvey, who found an increase in both plant pigments and cells; Ketchum has not detected an increase). In the Sound, this phenomenon may occur during periods when the quantity of nutrients has suddenly risen after having been at a low level for some time, and it is also common in the winter when the nutrient content is fairly high but the temperature is low. Such an increase is generally accompanied by a diminution or reversal of the normal processes of regeneration of *N* and *P* in the dark bottles. It is therefore evident that in the natural plankton association, as well as in laboratory experiments with pure cultures, the fixation of carbon and its conversion to protoplasmic substances are not necessarily coincident processes. The second may lag behind the first when physical or chemical conditions are not favorable for conversion. It is therefore hardly to be expected that the results of experiments on oxygen production and nitrogen consumption should coincide. When the Long Island Sound data on phytoplankton production are calculated in the way described above, the ratio of nitrate consumption to oxygen production varies from a negative value to about 110%, and the mean is 38%. The higher average here suggests that the Sound, with its greater concentration of nutrients, is less conducive to such phenomena than oceanic areas.

It is obvious that there is a limit to the amount of stored foodstuffs that a plant can accumulate. But if, as the calculations suggest, active photo-

synthesis at the surface for one day supplies the normal respiratory requirements for ten days, the phenomenon is likely to be important, for not only does it provide a mechanism for carrying the plant through periods of unfavorable nutritive conditions, but also it permits a lengthy existence as well as assimilation and growth below the euphotic zone. The latter would permit utilization of nutrients throughout a much longer column of water than is generally supposed, but whether this would increase or decrease the total productivity of the region would depend on the amount of turbulence. This and other ramifications of the theory suggest that it is a profitable subject for investigation.

ZOOPLANKTON

The zooplankton was collected in nets of No. 10 bolting silk, and the use of Clarke plankton samplers permitted the quantitative measurement of the amount of water strained. The results of the measurements are shown in Table III.

TABLE III

ZOOPLANKTON

Station	*Depth*	*Volume cc/m³*	*Nauplii and copepodites No./m³*	*Copepods No./m³*	*Misc. No./m³*	*Total No./m³*	*Total No./m²*
3486	0–150	0.02	130	230	20	380	116000
	150–300	0.02	160	200	30	390	
3492	0–100	0.05	160	700	90	950	95000
3511	0–150	0.07	240	760	50	1050	257000
	150–300	0.02	220	380	60	660	
3535	0–50	4.3	19000	29300	1500	49800	2490000
3537	0–25	8.1	5090	4580	2700	12370	309300

The counts are probably a more accurate estimate of the quantity of zooplankton than the volumes. The latter are distorted by the presence of enormous numbers of Ceratium and peridinians in the northern waters. The counts are also somewhat distorted, due to the usual qualitative variations. The miscellaneous groups in the southern waters, chiefly Sagitta, medusae, and decapod crustacean larvae, bulk larger than their number would indicate, but this is at least partly compensated by the larger average size of the northern copepod fauna, of which Calanus was a common constituent. When such small quantities of data are involved, such errors as these are generally of less importance than the sampling errors, and elaborate calculations of volume are not justified.

The number of animals per unit volume in the southern waters was about half as great as in the shallow waters of the Tortugas region. The latter were surface water determinations, and with more adequate sampling the

difference might be more marked. But since the plankton in the deeper water occupies a long vertical column, showing little diminution down to the 300 m. level, there is little doubt that the total crop of zooplankton is much greater in the open ocean than in the shallow areas.

The number of animals per unit volume in the southern waters was from 0.8% to 8.5% as great as in the northern shallows, represented by stations 3535 and 3537. The total crop per unit area, down to the limit of sampling, was 3.8 to 83% as great. It therefore appears that the northern waters, in which the total standing crop of phytoplankton and the total productivity are less than in the south, and in which the crop per unit volume is only two or three times as great, may support a considerably larger fauna. It is impossible to say whether such a conclusion is rational. It depends on the food requirements at different temperatures, feeding efficiency with different concentrations of food in the medium, and other matters too poorly understood at present to permit quantitative expression. Qualitatively, however, it may be stated a priori that the food requirements are greater in tropical waters, so that a larger crop of phytoplankton is needed to support a given number of animals. Moreover, the rate of turnover may be faster, in which case the comparison of relative abundance would not be an accurate statement of the zooplankton productivity.

Finally, it is of interest to note that Harvey, Cooper, Lebour, and Russell (1935) found in the English Channel an annual mean of between 2000 and 3000 animals per m^3 in the upper 45 m., and Russell (1934) reported that the number of animals in the Great Barrier Reef lagoon is approximately equal to the crop in the North Sea and the English Channel. The figures listed by Harvey and his associates give a total crop of 90,000 to 135,000 animals per m^2, which is of the same order of magnitude as the number found in the southern waters in the present work. It therefore is possible that the zooplankton content of these waters was not relatively low, but rather that the quantity in the northern shallows was unusually large, either because of high productivity or perhaps because the samples were taken during a peak period.

SUMMARY

1. Measurements were made of temperature, oxygen, plant pigments, phosphate and nitrate at eighteen stations in the western North Atlantic between the northern coast of Cuba and Woods Hole during May and the early part of June, 1939. In the surface water of all stations the chlorophyll content was determined, and analyses were made of the oxygen and nitrate production and consumption in experimental light and dark bottles.

2. The quantity of plant pigments at the four northernmost stations was greatest at the surface, and the maximum depth of occurrence was 100 m. or less. At the southern stations they occurred to a depth of 300 to 400 m. or

more, and the maximum observed values were at 100 m. The quantity of plant pigments in the surface water was three times as great in the north as in the south, and the amount of chlorophyll was twice as great. But the total crop in the entire vertical column was considerably greater in the southern waters.

3. The mean oxygen production in the northern waters was 0.180 mg. per liter per day, about half as much as the values recorded by previous workers for temperate shallow-water regions during the spring bloom. In the tropical waters the average was 0.091 mg. Fifty-five percent of the variations in oxygen production can be accounted for on the basis of differences in the quantity of the standing crop. Other factors—temperature, light, and nutrients—did not appear to have a significant effect. Although the gross productivity (glucose production) of the southern surface waters is only half as great as in the north, it is suggested that because of the greater transparency of the water, the maximum depth of photosynthesis is about three times as great, and the total productivity per unit area may be equal to or greater than that of temperate regions. Nitrate consumption was relatively much less than oxygen production, and rough estimates indicate that only 10 to 27% of the glucose produced was transformed into nitrogenous material during the course of the experiments. The theoretical biological implications of this phenomenon are discussed.

4. Quantitative measurements of zooplankton were made at five stations. The total number of animals was less in the tropical waters than at the northern stations but was about equal to the annual mean for certain other temperate regions, the English Channel and the North Sea, as well as the tropical waters of the Great Barrier Reef lagoon.

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TABLE IV

STATION LIST AND ANALYSES

	Depth	Temp.	Oxygen cc./l.	Oxygen % sat.	P mg. at. per m^3	N mg. at. per m^3	Plant pigments Harvey units/m^3	Chloro-phyll mgs./m^3
Station 3486								
5/11/39	1	26.63	4.68	99	0.18	1.00	3500	2.5
23° 13′ N, 81° 22′ W	100	25.87	4.56	95	0.09	0.50	3400	
Depth 722 m.	200	20.64	4.40	84	0.44	2.21	1800	
Station 3491	1	26.93	4.72	100	0.03	1.70	2000	1.5
5/15/39	100	25.37	4.43	92	0.06	0.31	1200	
23° 44′ N, 81° 46′ W	200	19.26	3.54	66	0.29	0.93	900	
Depth 1719 m.	300	16.82	3.78	67	0.59	14.3	600	
Station 3492	1	26.77	4.66	99	0.06	0.62	1400	0.9
5/16/39	48	24.41	4.88	100	0.05	0.62	1700	
25° 14′ N, 80° 05′ W	97	21.14	4.63	89	0.08	1.18	2900	
Depth 230 m.	184	10.40	2.90	46	1.82	18.2	700	
Station 3498	1	26.67	4.67	99	0.16	0.57	1700	1.3
5/21/39	98	25.26	4.45	92	0.09	0.36	2100	
25° 49′ N, 79° 35′ W	197	18.19	3.60	66	0.45	1.65	1600	
Depth 777 m.	296	14.27	2.91	50	1.08	9.1	1300	
Station 3500	1	26.66	4.63	98	0.14	2.00	1900	1.6
5/21/39								
25° 33′ N, 79° 19′ W								
Depth 17 m.								
Station 3510	1	26.38	4.67	98	0.04	0.10	900	0.9
5/23/39	94	22.31	4.78	96	0.00	0.00	2000	
26° 48′ N, 79° 47′ W	188	12.48	3.17	52	1.45	6.5	900	
Depth 357 m.	282	7.96	2.90	44	1.93	23.4	700	
Station 3511	1	26.31	4.60	97	0.16	1.80	800	0.7
5/24/39	87	24.06	4.42	90	0.17	1.34	2500	
31° 02′ N, 79° 18′ W	173	20.18	3.41	65	0.61	2.52	700	
Depth 732 m.	260	16.87	3.45	62	0.90	3.86	100	
Station 3512	1	26.53	4.54	96	0.00	2.42	900	0.6
5/25/39	100	24.31	4.06	82	0.12	2.21	2300	
33° 10′ N, 76° 34′ W	200	19.48	4.35	81	0.22	4.88	900	
Depth 704 m.	300	17.79	4.58	83	2.05	5.70	300	
Station 3513	1	23.98	5.00	101	0.02	0.67	700	0.5
5/26/39	100	20.68	5.02	96	0.05	0.15	1800	
34° 15′ N, 73° 11′ W	200	18.99	4.76	88	0.00	0.46	1000	
Depth 4471 m.	300	18.09	4.73	86	0.17	0.21	300	
Station 3514	1	21.99	5.22	102	0.00	2.00	1300	0.8
5/27/39	97	18.12	5.19	95	0.00	2.11	2200	
34° 48′ N, 69° 53′ W	193	17.96	5.13	94	0.02	3.96	1300	
Depth 5276 m.	290	17.82	5.03	91	0.05	2.83	400	
	386	17.42	4.59	83	0.29	7.0	<100	
Station 3515	1	22.90	5.10	101	0.01	0.87	800	0.6
5/28/39	97	19.67	5.09	95	0.01	0.98	1500	
35° 10′ N, 66° 50′ W	193	18.39	5.13	94	0.01	1.28	200	
Depth 5148 m.	290	18.09	5.17	94	0.04	4.57	200	
	386	18.11	5.19	95	0.08	1.64	100	
Station 3517	1	22.05	5.22	102	0.00	3.44	600	0.4
5/29/39	100	18.32	5.12	94	0.07	1.80	1500	
35° 54′ N, 67° 34′ W	201	18.02	5.06	92	0.04	2.05	400	
Depth > 4000	301	17.67	4.92	89	0.12	4.57	200	
	402	17.18	4.72	85	0.24	2.42	<100	

TABLE IV—*Continued*

STATION LIST AND ANALYSES

	Depth	Temp.	Oxygen cc./l.	Oxygen % sat.	P mg. at. per m^3	N mg. at. per m^3	Plant pigments Harvey units/m^3	Chlorophyll mgs./m^3
Station 3520	1	23.14	5.02	100	0.04	0.67	900	0.7
5/30/39	100	19.40	5.04	94	0.00	1.03	1500	
37° 02′ N, 68° 43′ W	201	18.23	5.16	94	0.04	0.77	500	
Depth >4000	301	18.10	5.18	94	0.00	0.82	400	
	402	17.81	4.87	88	0.10	3.24	100	
Station 3523	1	25.10	4.90	101	0.03	0.46	800	0.6
5/31/39	102	21.47	4.44	86	0.07	1.44	1200	
37° 49′ N, 69° 18′ W	203	18.47	4.37	80	0.10	0.67	1000	
Depth >4000	305	17.13	4.17	75	0.20	1.13	300	
	407	14.84	3.72	64	1.01	8.8	100	
Station 3528	1	19.67	5.53	102	0.05	0.10	3200	1.4
6/1/39	45	14.35	5.54	94	0.12	0.46	2300	
38° 51′ N, 70° 04′ W	91	14.47	5.26	89	0.29	0.62	200	
Depth 2963 m.	181	13.08	4.32	71	1.17	8.6	<100	
	272	10.69	3.24	51	1.62	18.8	<100	
Station 3532	1	11.95	6.86	111	0.25	0.10	8300	3.6
6/2/39	23	10.20	6.15	96	0.45	0.41	3100	
39° 51′ N, 70° 53′ W	45	11.45	5.87	94	0.40	0.31	300	
Depth 969 m.	91	11.90	5.35	86	0.53	1.28	<100	
	181	11.41	5.30	58	1.35	10.8	<100	
Station 3535	1	10.63	7.05	111	0.15	0.26	1700	1.2
6/2/39	25	8.55	7.65	115	0.18	0.15	2700	
40° 22′ N, 71° 21′ W	50	6.64	6.53	95	0.57	0.87	700	
Depth 82 m.								
Station 3537	1	12.52	6.63	108	0.20	0.31	3300	2.0
6/3/39	10	10.61	7.23	114	0.13	0.41	3300	
40° 52′ N, 71° 50′ W	25	5.84	6.01	86	0.80	0.41	3200	
Depth 38 m.								

TRANSPORT AND CONVERGENCE OF THE NORTH ATLANTIC DRIFT CURRENT COMPUTED FROM THE AVERAGE JANUARY PRESSURE DISTRIBUTION*

By

EDWARD M. BROOKS

According to Montgomery (1936, 1938), one of the important effects of the wind blowing over the sea surface is its production of positive and negative convergence in the drift current, which is essentially limited to a surface homogeneous layer usually less than 50 meters thick. This convergence results from the net transport of the drift current at right angles to the wind, the magnitude of the transport being such that the deflecting force acting on it exactly compensates the wind stress. Of course, this involves the assumption that the drift current has come to equilibrium with the wind. To avoid boundary conditions, this theory should be applied only to the open ocean, away from coast lines and in deep water.

The purpose of this paper was to find the extreme variations of the transport and convergence of the drift current in the North Atlantic Ocean for average atmospheric conditions. Computations for January were carried out and compared with the results of Montgomery's investigation for July (Montgomery, 1936). Then the transport and convergence of the drift for the other months were estimated qualitatively from Defant's monthly average atmospheric pressure charts (Defant, 1917).

Two methods were employed in getting the January results. The first, following that used by Montgomery (1936), was based on gradient winds deduced from the January pressure distribution given by Defant (1917); whereas the second used direct wind observations collected by the Koninklijk Nederlandsch Meteorologisch Instituut (1919). As the first method has been adequately treated by Montgomery, only the second will be discussed here.

The wind speeds, which were estimated in Beaufort numbers, were converted into meters per second by use of the international Beaufort scale (Perlewitz, 1935). The formula used for getting the magnitude of the transport from the wind speed was

$$T = \frac{\tau_0}{f} = \frac{\rho\gamma^2 W_0^2}{2\Omega \sin L}$$

(Rossby and Montgomery, 1936), where T was the magnitude of the transport; τ_0, the shearing stress between wind and water; f, the Coriolis param-

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eter; ρ, the density of the air; γ^2, a stress coefficient; W_0, the surface wind speed; Ω, the angular velocity of the earth's rotation; and L, the latitude. γ^2 was taken as 0.0025 to conform with the choice of $z_0 = 0.6$ cm., used in the computations from Defant's pressures.

The transport and convergence calculated by the wind observations method were on the average about 20% larger than those obtained by the pressure method. Although this difference might be more marked if it were not for the existence of some atmospheric stability tending to reduce the surface wind speed below its theoretical value for a homogeneous atmosphere, the order of magnitude of the discrepancy seems relatively insignificant in view of the uncertainty of the applicability of the theory behind either computation. A second difference of more interest is the greater irregularity of the transport vectors and convergence magnitudes obtained from the wind method. It is doubtful whether the irregularities in the average winds can be explained by such atmospheric features as fixed anticyclonic cells in the Azores "high" or a mean polar front at a certain distance off the American coast because the positions of such semi-permanent elements might be too variable. Both of the differences found must be largely due to the fact that Defant got pressure values by interpolation with smoothed isobars, whereas the Dutch institute tabulated all observations without regard for geographical continuity.

The January transport and convergence computed from the average pressures of Defant are presented in Table I and Figure 52. The resemblance of the January chart to the July chart is quite pronounced in regard to both the distribution of the transport vectors and the magnitudes of the convergence, largely due to the existence of prevailing westerly winds in the north portion and easterly trades in the south portion at both times of year. On the other hand, minor seasonal differences in drift current movement occur in connection with the difference in size and shape of the Azores "high," which is less circular and has a weaker central pressure in January than in July. The average January transport is generally larger than that of July, corresponding to greater strength of the Icelandic "low" and steeper pressure gradients in the trade-wind belt in January. Along the average high pressure belt convergence is smaller, and in the extreme south it is larger than in July. Also, negative convergence, or divergence, is more marked in the Newfoundland region in January, when the mean isobars have a definite cyclonic curvature.

Although Defant's monthly average pressure maps suggest that the January and July conditions stand at opposite extremes in the annual cycle of average pressure distribution, the changes from one month to the other are not strictly uniform, as indicated by the maps for intervening months. Consequently, the annual trend of the more important features of the drift current deserves analysis from the monthly maps, even though the total variations are small.

By use of the principle that the transport is directly correlated with the wind speed, and that the convergence is positive in an atmospheric "high" pressure area and negative in a "low," it is possible to discuss the annual variations which might be expected. In the trade-wind belt, the northward transport is largest in winter, but the maximum convergence comes in the early spring; while the minimum (though still large) transport and con-

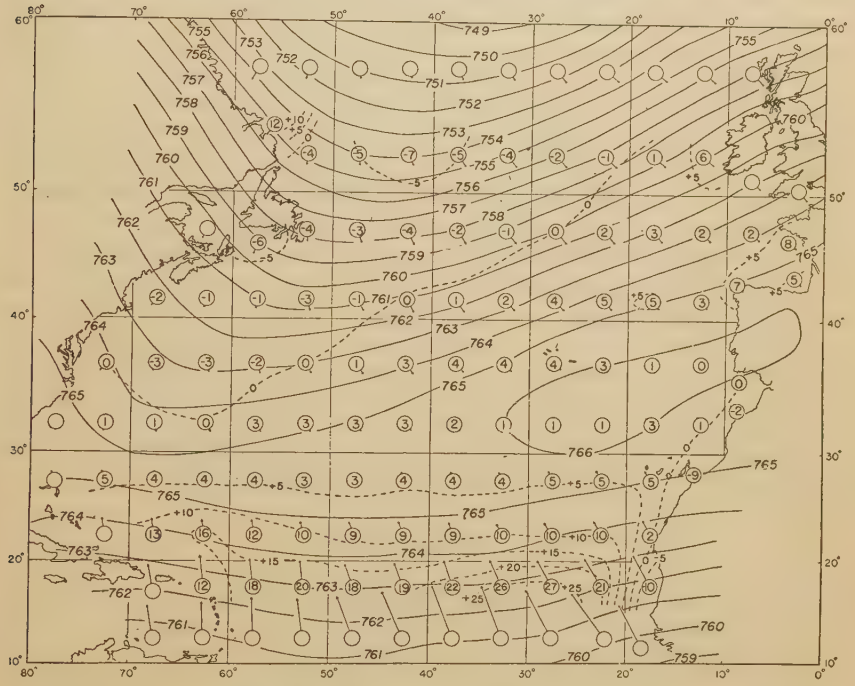

Figure 52. The solid lines are average January isobars for each mm. Hg of atmospheric pressure. The vectors represent the transport of the drift current at the center of each 5° square. The figures in circles give the convergence of the drift current in cm./day. The dotted lines connect areas of equal convergence.

vergence occur in autumn, when the pressure gradient is weakest and the isobars have the least anticyclonic curvature. Along the ridge of the Azores "high," convergence is pronounced in May and again in December, when there is a secondary maximum. In the zone of the westerlies, the greatest transport (always toward the south) occurs in late autumn and in early winter, but the convergence is largest in the spring months, although even then divergence exists east of Newfoundland. The American coastal transport is most marked in the latter part of the winter, when the maximum

divergence occurs. There is little divergence in summer, when the trough of low pressure moves onto the continent. Along the African coast, divergence is most pronounced when the transport is directed as much off-shore as possible, which is the case in spring. In general, the magnitude of this divergence is directly correlated with the magnitude of the convergence in the trade-wind belt.

In conclusion, it might be stated that the characteristics of the average drift current were found to be more nearly constant during the year than might have been previously expected. However, it is obvious that, since a wind distribution and a corresponding atmospheric pressure field do not strictly match each other due to accelerations of the air, lateral atmospheric friction, and thermal stability, this sort of analysis could be improved by more accurate wind observations over a conveniently restricted area in the open ocean, for it is the actual wind rather than the pressure gradient which affects the drift current. To make best use of such wind observations, it would be necessary to apply a "smoothing" process similar to the smoothing of isobars, which process at the same time would not wipe out any real atmospheric discontinuities existing under average conditions. To test how closely the average is represented at any particular time, it might be advisable to compute the transport and convergence by days from a series of synoptic situations given on weather maps. The results of such a study might indicate, in addition to the average flow and convergence, possible temporary anomalies of the drift current configuration, which in some cases might appear in the form of incipient eddies with vertical axes.

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TABLE I

MAGNITUDE (TONS/METER/SEC) AND DIRECTION (CLOCKWISE FROM N) OF THE TRANSPORT OF THE DRIFT CURRENT FOR JANUARY

	80° W.		70° W.		60° W.		50° W.		40° W.		30° W.		20° W.		10° W.		0°		10° E.	
60° N.					0.58 212°	0.34 197°	0.21 177°	0.21 169°	0.29 159°	0.37 148°	0.56 141°	0.67 131°	0.61 130°	0.62 132°	0.62 139°	0.53 141°	0.47 129°	0.25 124°		60° N.
50° N.					0.43 214°	0.33 192°	0.35 175°	0.38 158°	0.50 148°	0.56 143°	0.61 139°	0.63 136°	0.57 134°	0.48 131°	0.39 135°	0.37 140°	0.43 140°	0.44 —		50° N.
		0.11 —	0.16 221°	0.26 209°	0.37 204°	0.32 179°	0.44 162°	0.58 155°	0.60 145°	0.65 141°	0.64 139°	0.57 138°	0.45 139°	0.35 138°	0.25 133°	0.16 130°	0.10 119°			
40° N.		0.19 218°	0.11 218°	0.08 195°	0.19 194°	0.34 162°	0.44 151°	0.50 151°	0.50 145°	0.49 139°	0.45 138°	0.34 140°	0.22 146°	0.14 145°	0.11 140°	0.09 138°				40° N.
	0.08 217°	0.16 224°	0.14 202°	0.17 167°	0.27 161°	0.31 153°	0.34 146°	0.36 146°	0.31 139°	0.22 138°	0.12 135°	0.07 145°	— —	— —	— —					
30° N.	0.03 228°	0.09 199°	0.15 180°	0.21 153°	0.23 152°	0.20 151°	0.13 144°	0.07 137°	0.04 129°	— —	— —	— —	0.04 305°	0.05 307°	0.04 317°					
	0.14 341°	0.08 350°	0.03 351°	— —	— —	— —	— —	0.03 343°	0.08 340°	0.12 333°	0.22 337°	0.31 331°	0.33 331°	0.23 330°						30° N.
20° N.	0.70 —	0.65 351°	0.61 352°	0.53 354°	0.57 352°	0.48 347°	0.48 342°	0.52 340°	0.45 339°	0.43 332°	0.52 327°	0.58 332°	0.65 331°							
		1.44 —	1.52 349°	1.72 354°	1.52 352°	1.35 352°	1.21 341°	1.28 339°	1.46 341°	1.57 336°	1.65 331°	1.83 330°	2.03 331°							20° N.
			1.84 350°	2.06 359°	2.42 358°	2.37 352°	2.66 340°	3.15 337°	3.48 339°	3.49 339°	3.43 332°	3.50 323°	2.99 332°							
10° N.																				10° N.

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